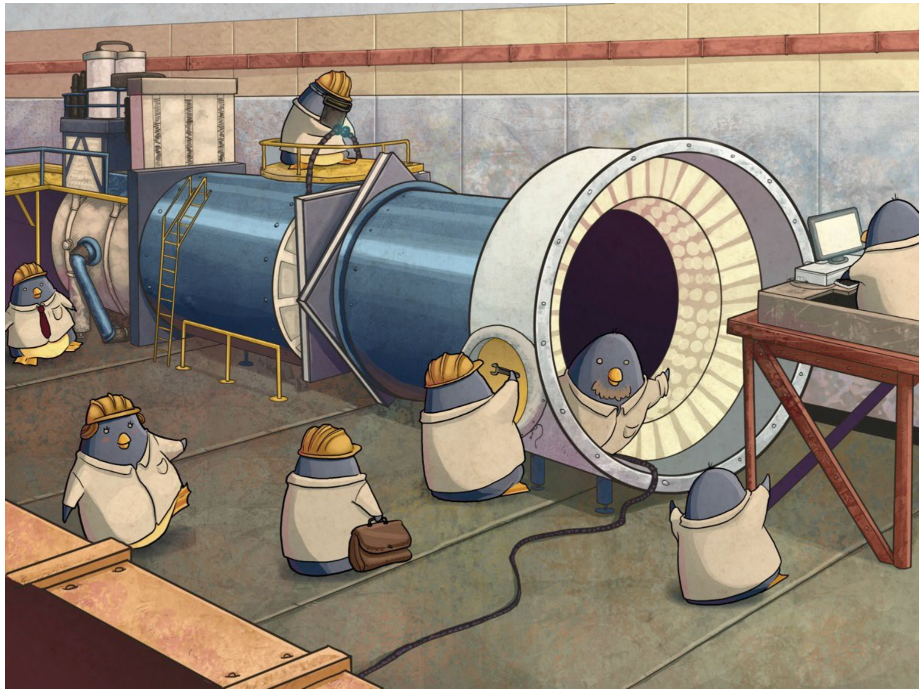
Recent results from the NA62 experiment

Jacopo Pinzino

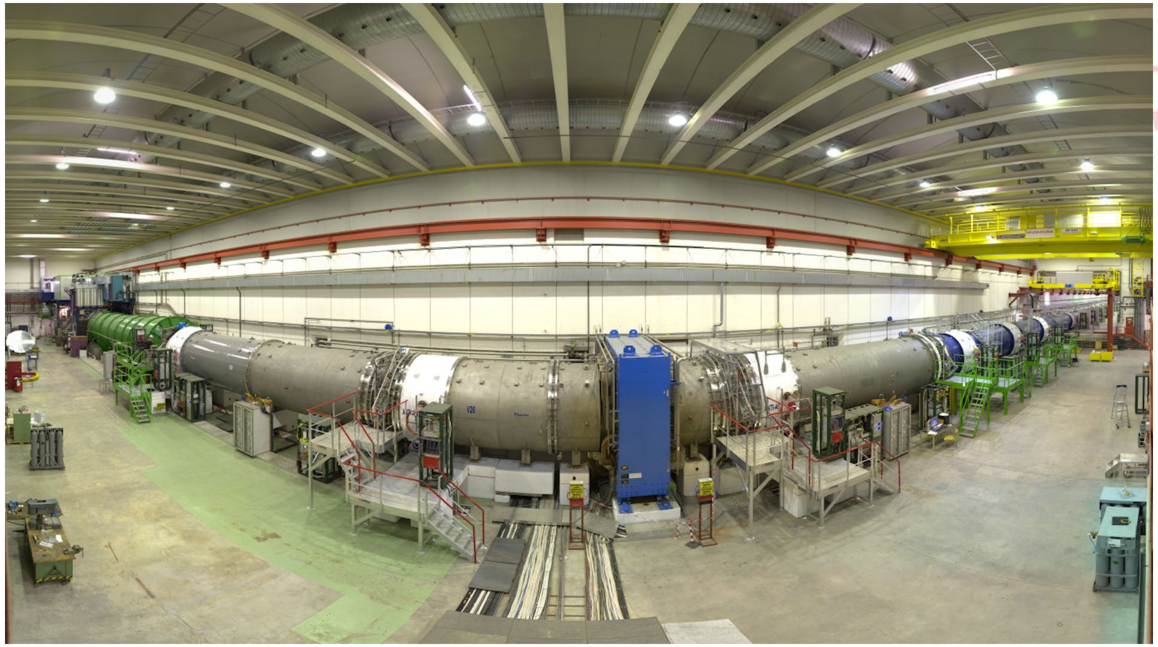


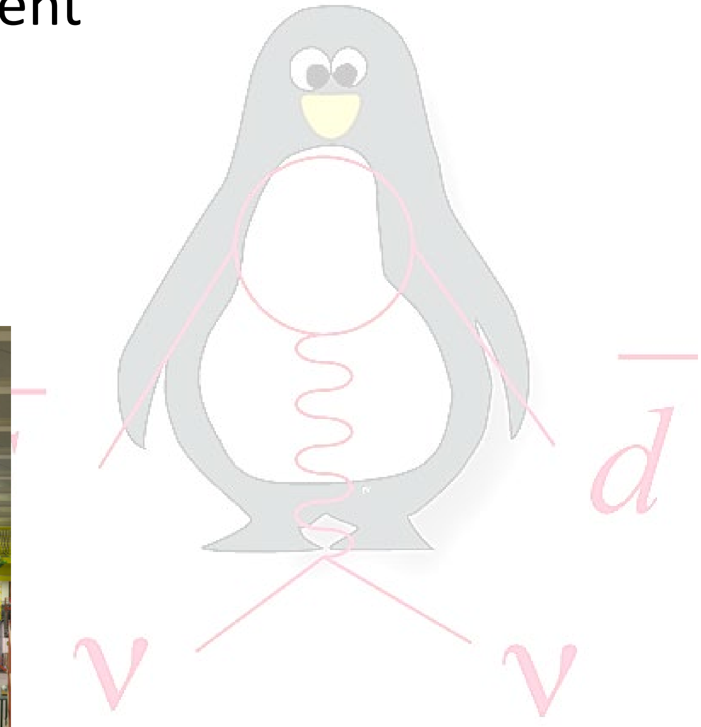
INFN Pisa

Triggering Discoveries in
High Energy Physics III
12/12/24

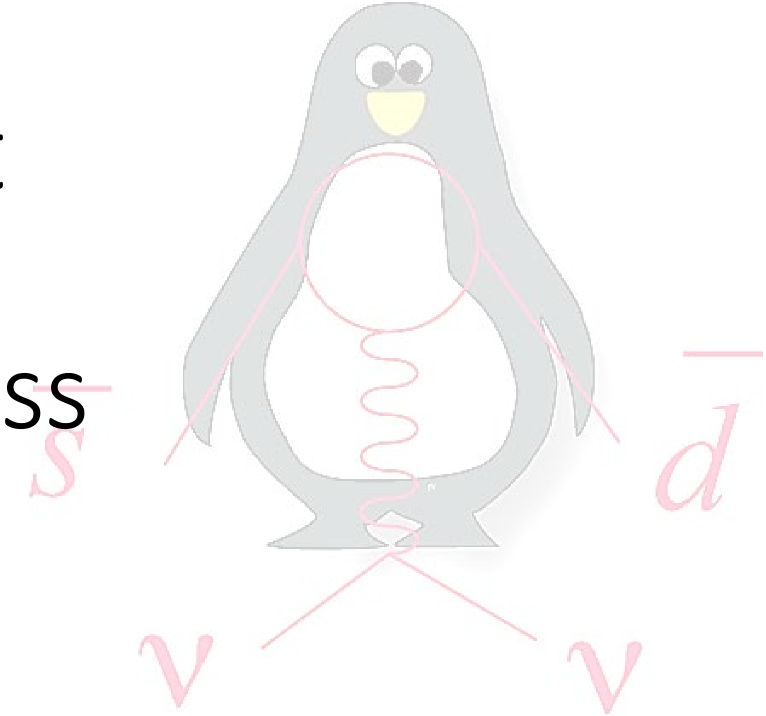
Outline

- The NA62 Experiment and the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ process
- RUN2 upgrades
- Last updates about the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ measurement
- LNV / LFV SEARCHES
- Rare Kaon and Pion Decays
- Long-Lived NP Particles: hadronic final state





The NA62 Experiment
And
the $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$ process



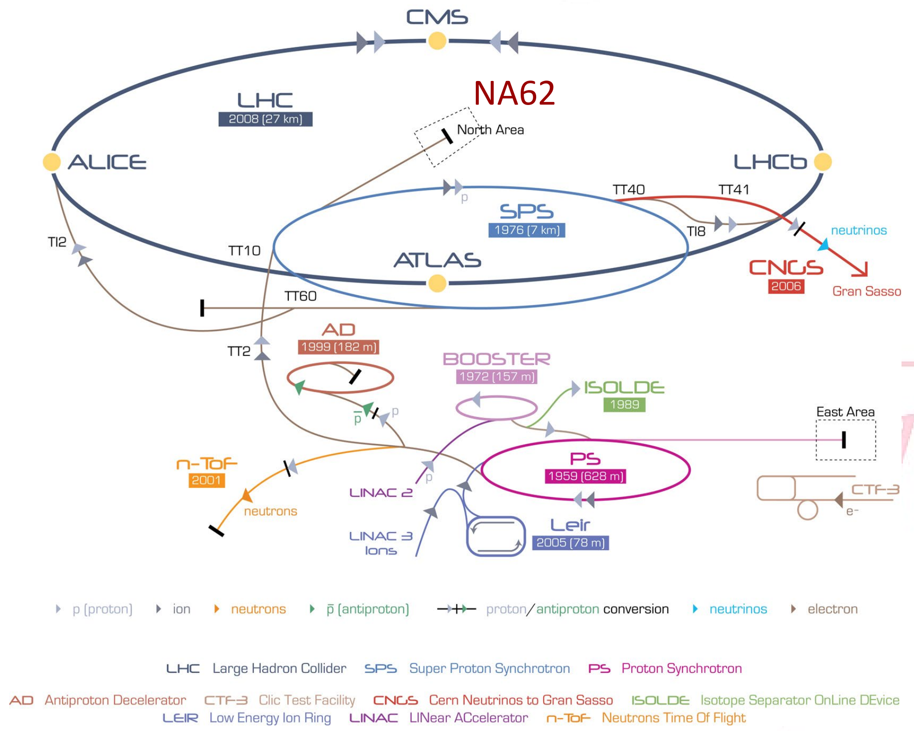
The NA62 Experiment

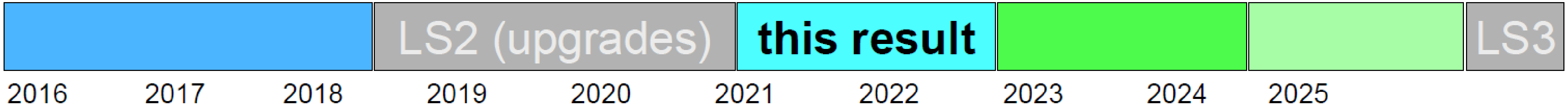
- NA62: High precision fixed-target Kaon experiment at CERN SPS
- Main goal: measurement of BR($K^+ \to \pi^+\nu\bar{\nu}$)
- Broader physics program: LFV / LNV in K^+ decays, precision measurements and hidden sector particles searches.

~ 200 participants from: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Torino, TRIUMF, Vancouver UBC

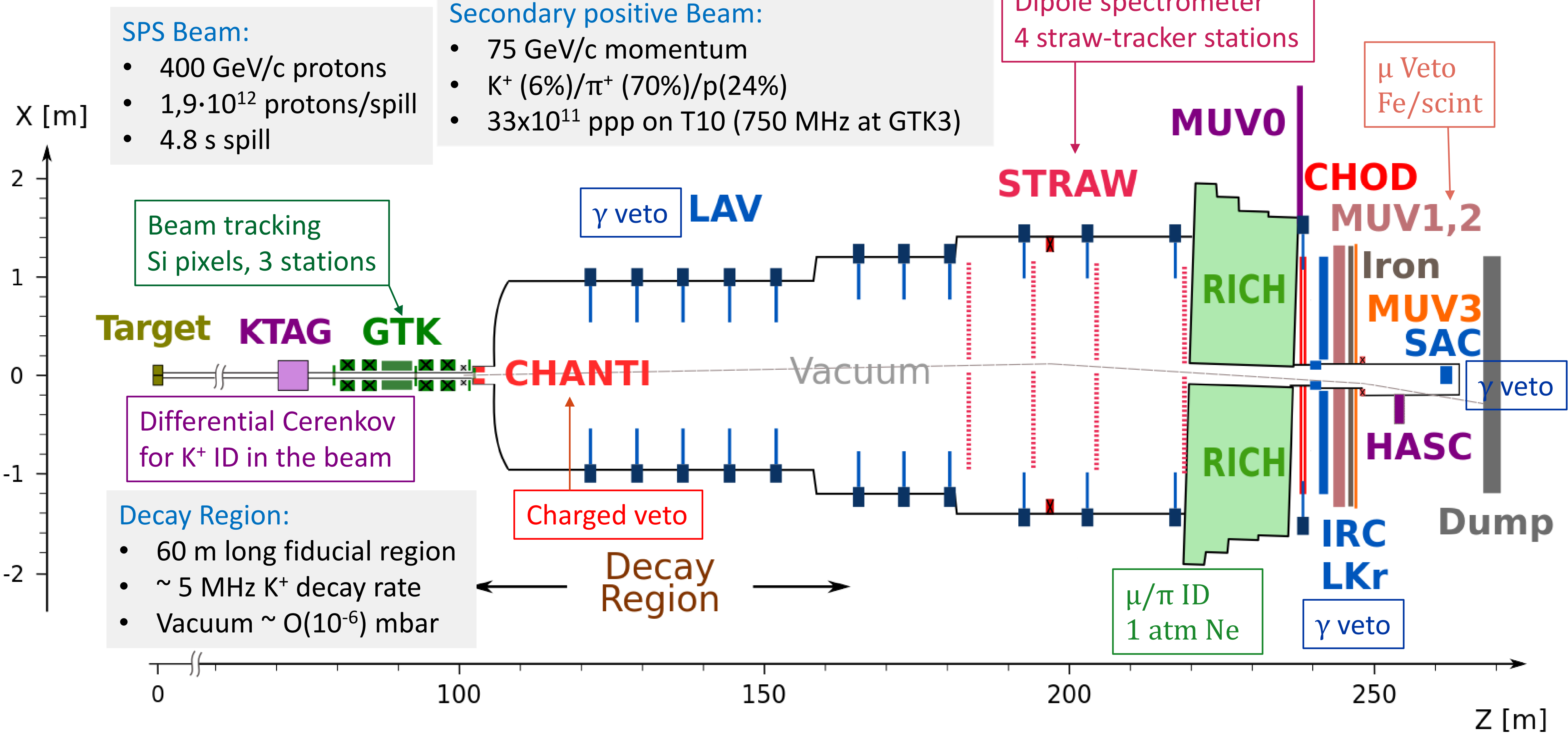
NA62 Timeline

- 2008: NA62 Approval
- 2014: NA62 Pilot Run (partial layout)
- 2015: Commissioning run
- 2016 Commissioning + Physics run (45 days)
- 2017 Physics run (160 days)
- 2018 Physics run (217 days)
- 2021 Physics run (85 days [10 beam dump])
- 2022 Physics run (215 days).
- 2023 Physics run (150 days [10 beam dump]).
- 2024 Physics run just finished (204 days [10 beam dump]).





NA62 Layout


SPS Beam:
• 400 GeV/c protons
• 1,9·10^12 protons/spill
• 4.8 s spill
Secondary positive Beam:
• 75 GeV/c momentum
• K+ (6%)/π+ (70%)/p(24%)
• 33x10^11 ppp on T10 (750 MHz at GTK3)
Dipole spectrometer
4 straw-tracker stations
μ Veto
Fe/scint
X [m]
2
1
0
-1
-2
MUV0
STRAW
CHOD
MUV1,2
γ veto
LAV
Beam tracking
Si pixels, 3 stations
Iron
MUV3
SAC
Target
KTAG
GTK
RICH
CHANTI
Vacuum
γ veto
Differential Cerenkov
for K+ ID in the beam
RICH
HASC
Decay Region:
• 60 m long fiducial region
• ~ 5 MHz K+ decay rate
• Vacuum ~ O(10^-6) mbar
Charged veto
Decay
Region
IRC
LKr
Dump
μ/π ID
1 atm Ne
γ veto
0
100
150
200
250
Z [m]

NA62 Trigger

NA62 aims to measure the ultra-rare decay $BR(\pi\nu\nu)_{Buras} = 8.60 \times 10^{-11}$

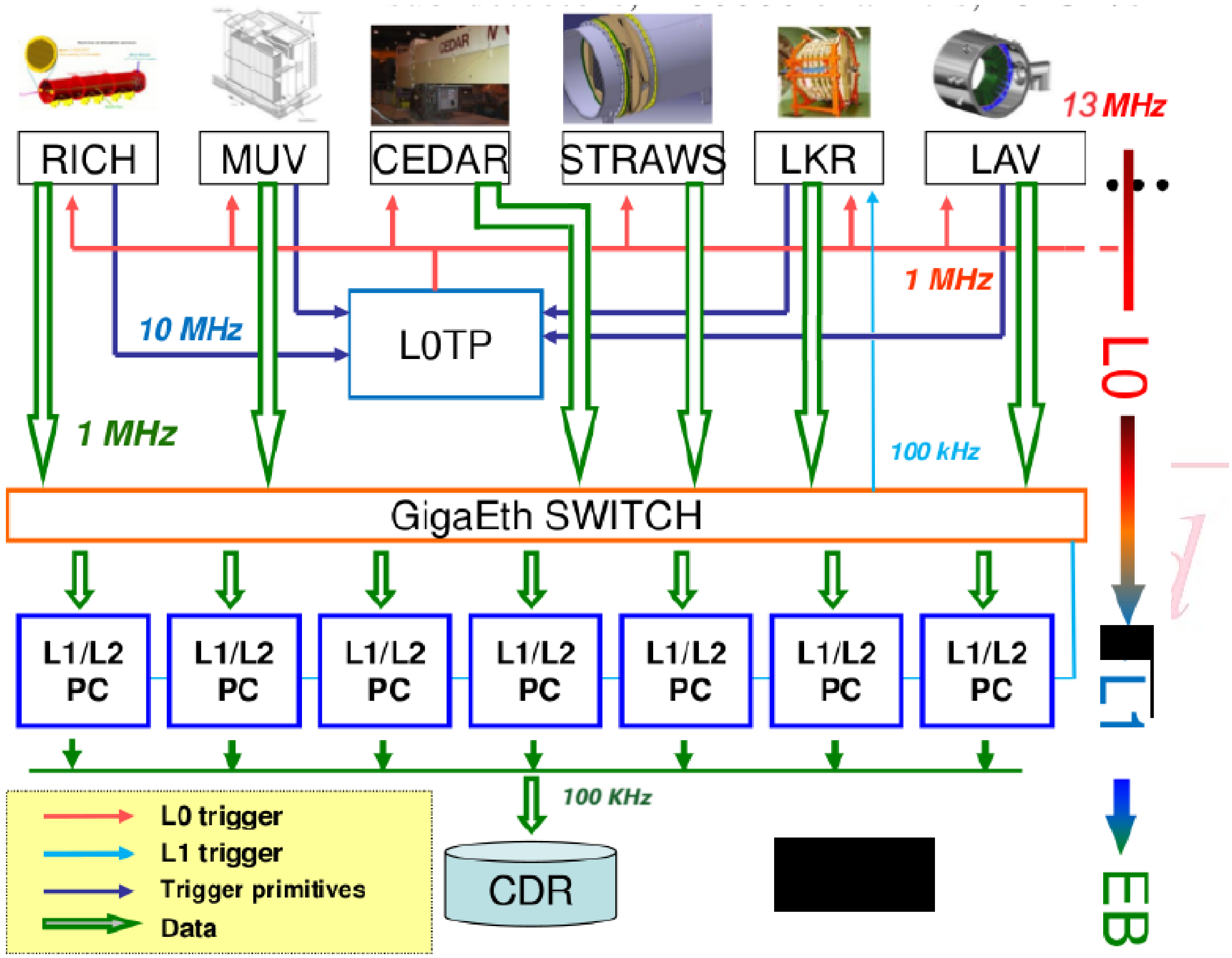
Very intense hadron beam:

- close to a GHz upstream
- more than 13 MHz of Kaon decays
- spills of 4.8s duration

- good time resolution at level L0
- a fast, selective trigger and data acquisition system
- minimization of data-collection dead times

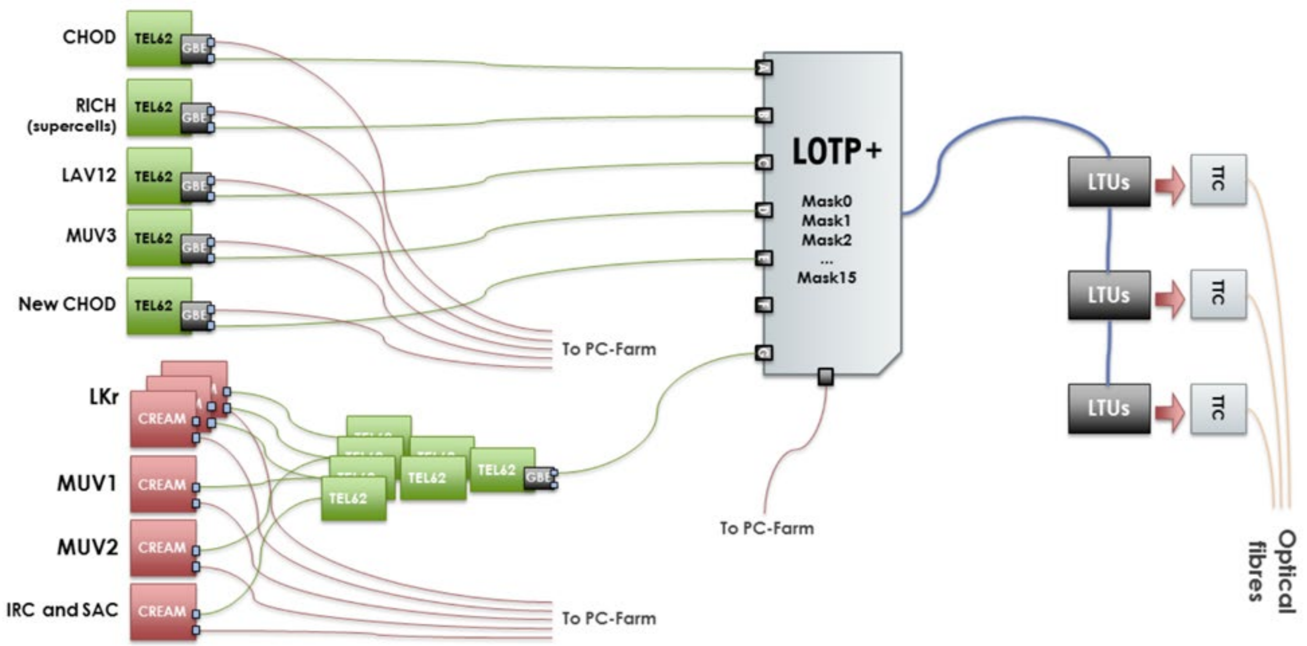
2 trigger levels:

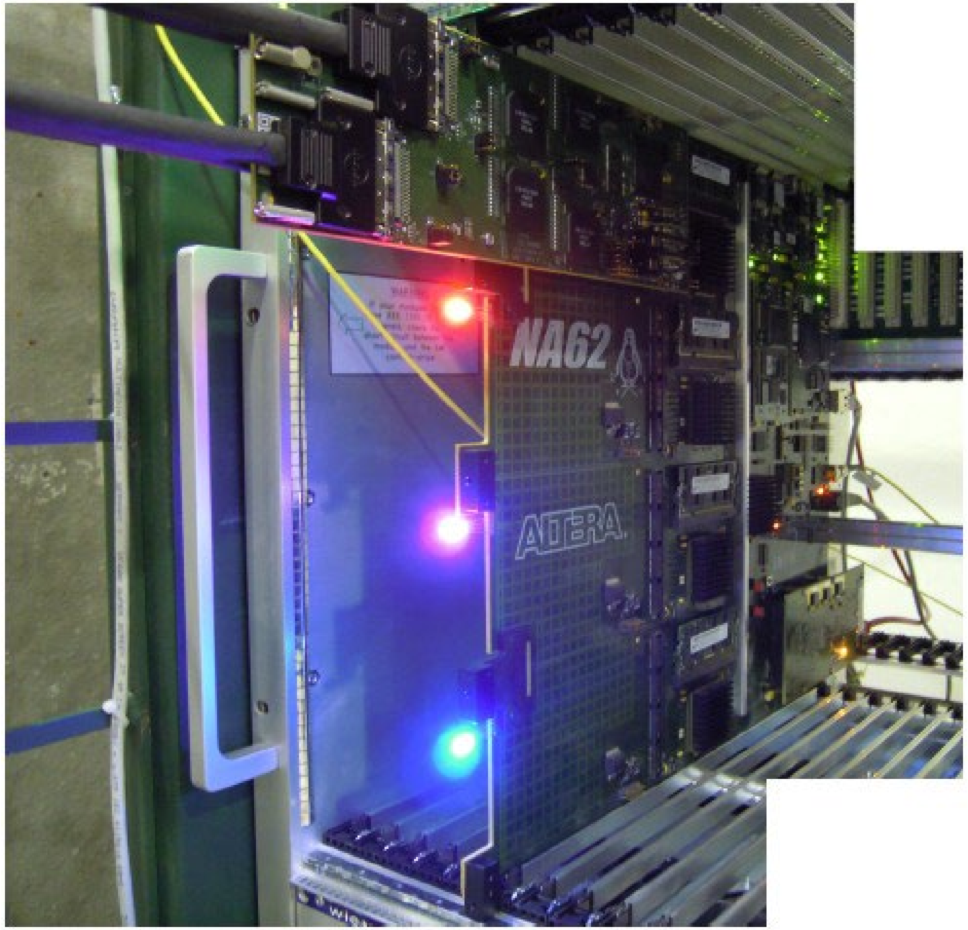
- hardware level: **level-0 trigger**
- software level: **level-1 trigger**



L0 Trigger

- Some detectors send raw data (***primitives***) to the level-0 trigger processor L0TP+;
    - Primitives are generated from the TEL62 read out boards;
- L0TP+ combine primitive in time to generate trigger requests
- L0 trigger request are sent through TTC system
- L0 trigger is generated after a **maximum latency of 1 ms;**
- All detectors except Calorimeters and GTK respond to L0;
- 10 L0 trigger masks.
- L0 efficiency $> 92\%$





L1 Trigger

- L1 Algorithms based on 3 detectors data: KTAG, LAV and STRAW;
- L1 trigger run over a cluster of 30 computers, with each computer independently executing the software on a subset of the L0-triggered events.
- Calorimeters and GTK send data after L1 request;
- A fraction (1%) of the events are accepted regardless the trigger condition for efficiency measurement
- L1 efficiency ~ 98%
- Events size ~ 20 kB

burst length: ~ 4.8 sec

↓

protons on target: 3.3×10^{12}

↓

Secondary beam: 750 MHz

↓

L0 input: >10 MHz

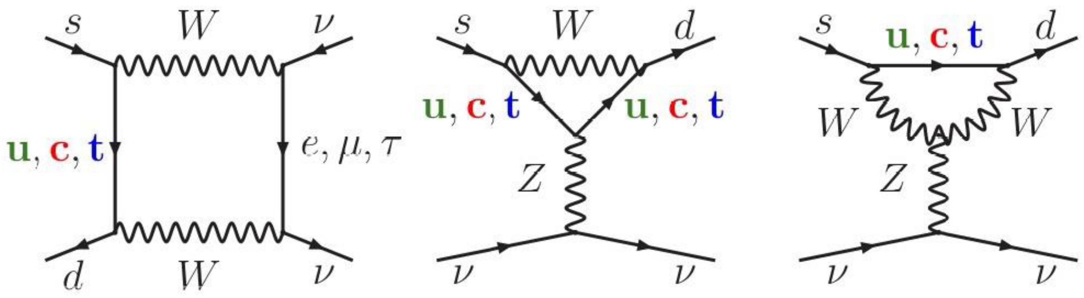
↓

L0 output: 1 MHz

↓

L1 output: 100 kHz

The $K^+ \to \pi^+ \nu \bar{\nu}$ decay



- High sensitivity to New Physics
- FCNC process forbidden at tree level
- Highly CKM suppressed (BR ~ $|V_{ts} x V_{td}|^2$)

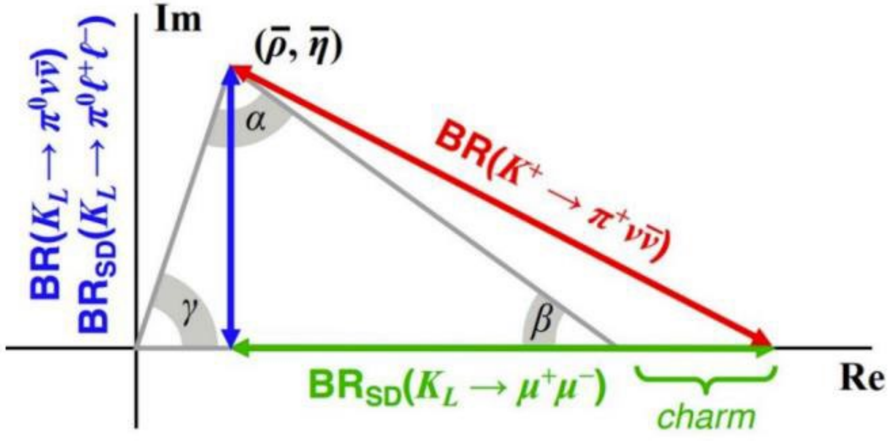
- Very clean theoretically: Short distance contribution
- hadronic matrix element extracted from precisely measured BR($K^+ \to \pi^0 e^+ \upsilon$)
- Precise SM predictions:
  - $BR(K^+ \to \pi^+ \upsilon\bar{\upsilon})_{Buras} = (8.60 \pm 0.42) \times 10^{-11}$

    [Buras et al. EPJC 82 (2022) 7, 615]
  - $BR(K^+ \to \pi^+ \upsilon\bar{\upsilon})_{D'ambrosio} = (7.86 \pm 0.61) \times 10^{-11}$

    [D'Ambrosio et al. JHEP 09 (2022) 148]
- Experimental status:

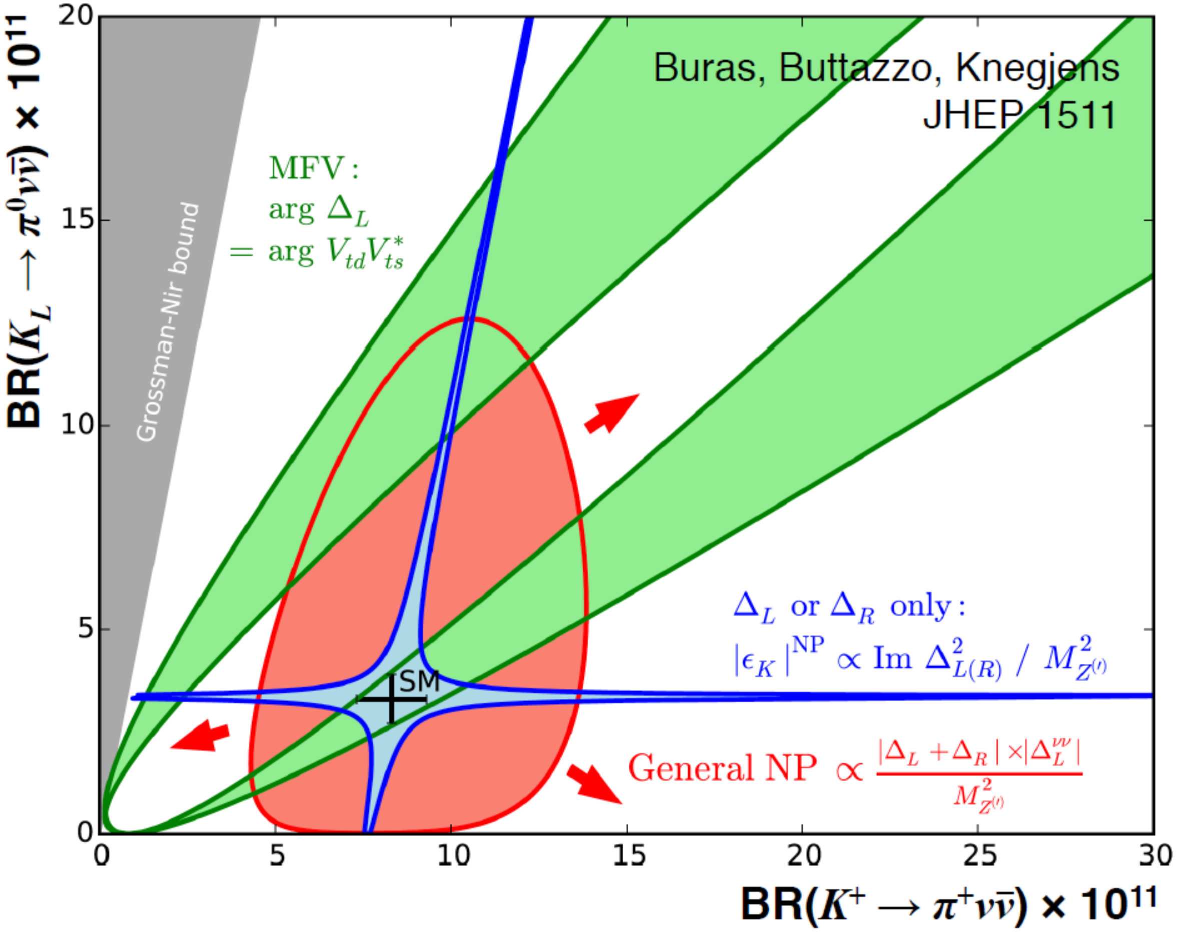
  $BR(K^+ \to \pi^+ \upsilon\bar{\upsilon})_{NA62(2016\text{-}18\ data)} = (10.60^{+4.1}_{-3.5}) \times 10^{-11}$

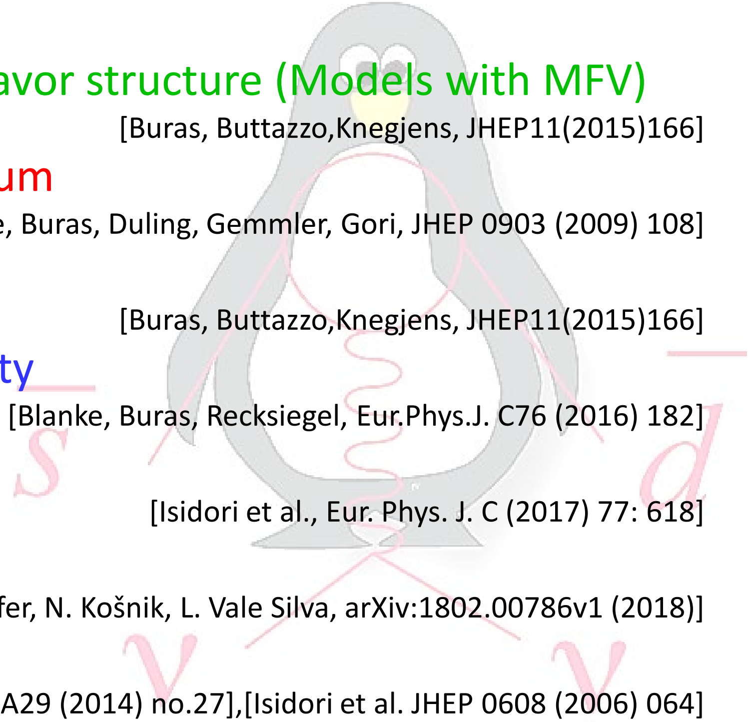
  [JHEP 06 (2021) 093]



$K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$ and New Physics

Measurement of charged ($K^+ \rightarrow \pi^+\upsilon\bar{\upsilon}$) and neutral ($K_L \rightarrow \pi^0\upsilon\bar{\upsilon}$) modes can **discriminate among different NP scenarios**





- Models with CKM-like flavor structure (Models with MFV)
  [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Custodial Randall-Sundrum
  [Blanke, Buras, Duling, Gemmler, Gori, JHEP 0903 (2009) 108]
- Simplified Z, Z' models
  [Buras, Buttazzo,Knegjens, JHEP11(2015)166]
- Littlest Higgs with T-parity
  [Blanke, Buras, Recksiegel, Eur.Phys.J. C76 (2016) 182]
- LFU violation models
  [Isidori et al., Eur. Phys. J. C (2017) 77: 618]
- Leptoquarks
  [S. Fajfer, N. Košnik, L. Vale Silva, arXiv:1802.00786v1 (2018)]
- MSSM analyses
  [Blazek, Matak, Int.J.Mod.Phys. A29 (2014) no.27],[Isidori et al. JHEP 0608 (2006) 064]

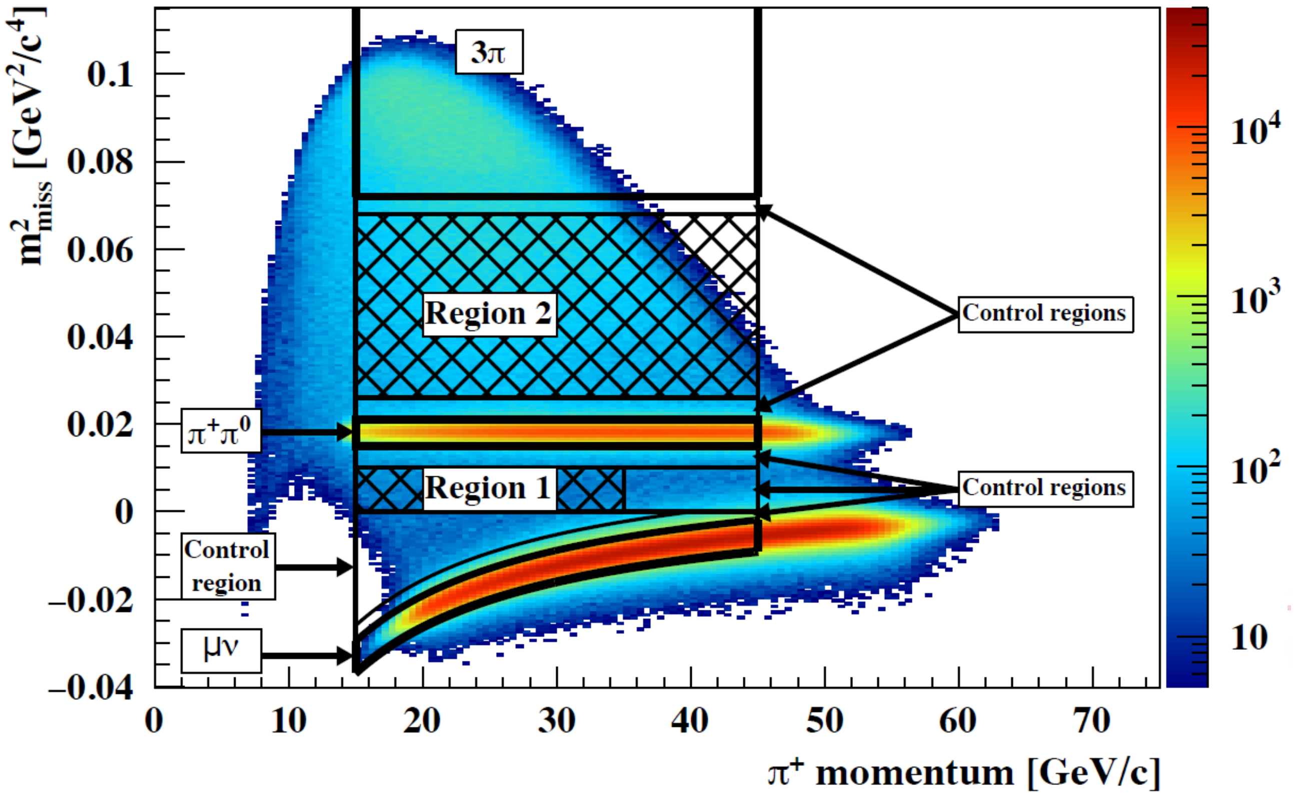
Analysis strategy

analysis key points:

- highly boosted decay (γ ~ 150)
- Large undetectable missing energy (neutrinos)
- All energy from visible particles must be detected
- Hermetic detector coverage
- 2 signal regions in m^2_{miss}
- $15 < P_{\pi^+} < 45$ GeV/c
- 60 m long decay region

Performance:

- 10^{-3} GeV²/c⁴ m^2_{miss} resolution
- $> 10^3$ kinematic background suppression
- $> 10^8$ Muon suppression
- $> 10^8$ π^0 (from $K^+ \to \pi^+\pi^0$) suppression
- O(100 ps) timing between sub-detectors



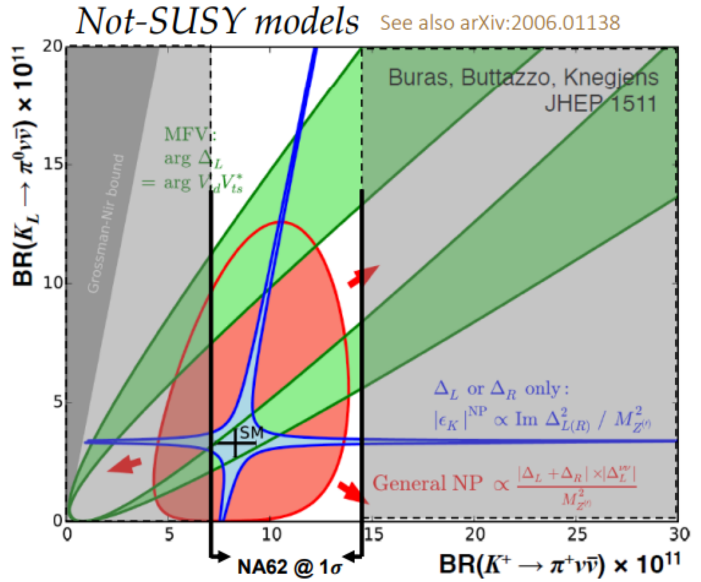
Process	*Branching ratio*
$K^+ \to \pi^+\pi^0(\gamma)$	0.2067
$K^+ \to \mu^+\nu(\gamma)$	0.6356
$K^+ \to \pi^+\pi^+\pi^-$	0.0558
$K^+ \to \pi^+\pi^-e^+\nu$	$4.25 \cdot 10^{-5}$

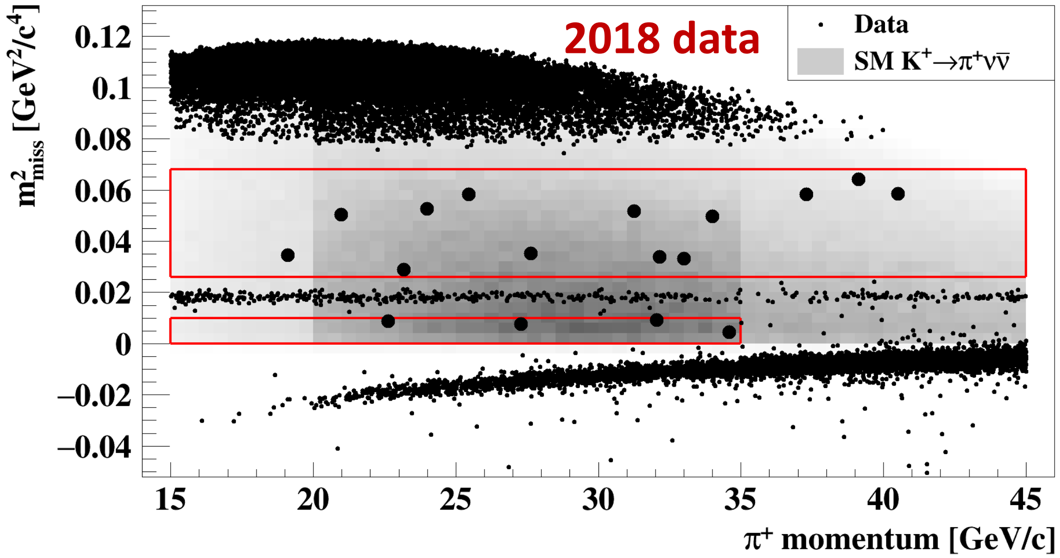
$K^+ \to \pi^+ \nu\bar{\nu}$: RUN1 result (2016 -2018)

[JHEP 06(2021) 093]

Data-taking year	[Reference]	N_{bg}	$N_{\pi\nu\bar{\nu}}^{SM,exp}$	N_{obs}
2016	[PLB 791 (2019) 156]	$0.152^{+0.093}_{-0.035}$	0.267 ± 0.020	1
2017	[JHEP 11 (2020) 042]	1.46 ± 0.33	2.16 ± 0.13	2
2018	[JHEP 06 (2021) 093]	$5.42^{+0.99}_{-0.75}$	7.58 ± 0.40	17
2016–18	[JHEP 06 (2021) 093]	$7.03^{+1.05}_{-0.82}$	10.01 ± 0.42	20

$N_{\pi\nu\bar{\nu}}^{SM,exp}$ assumes:
$\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$



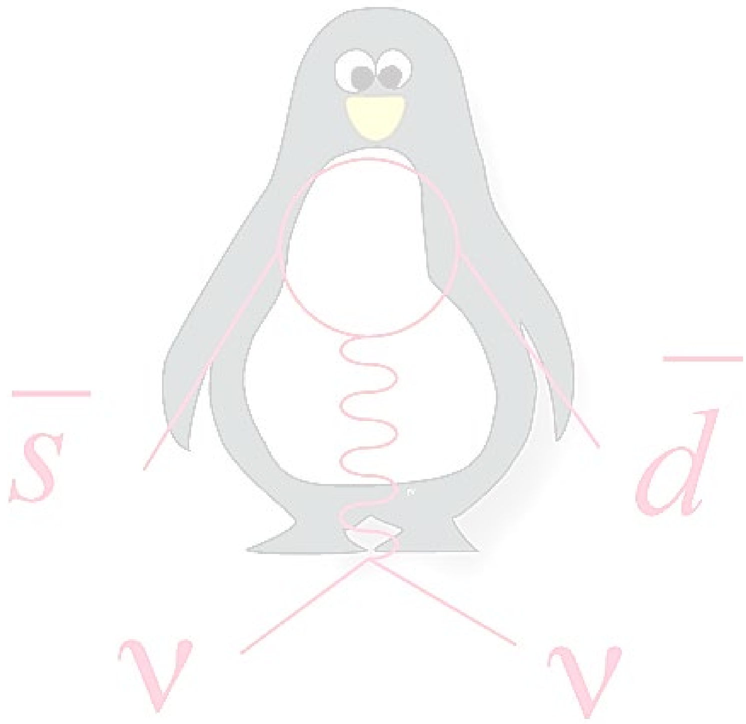


Statistical combination:

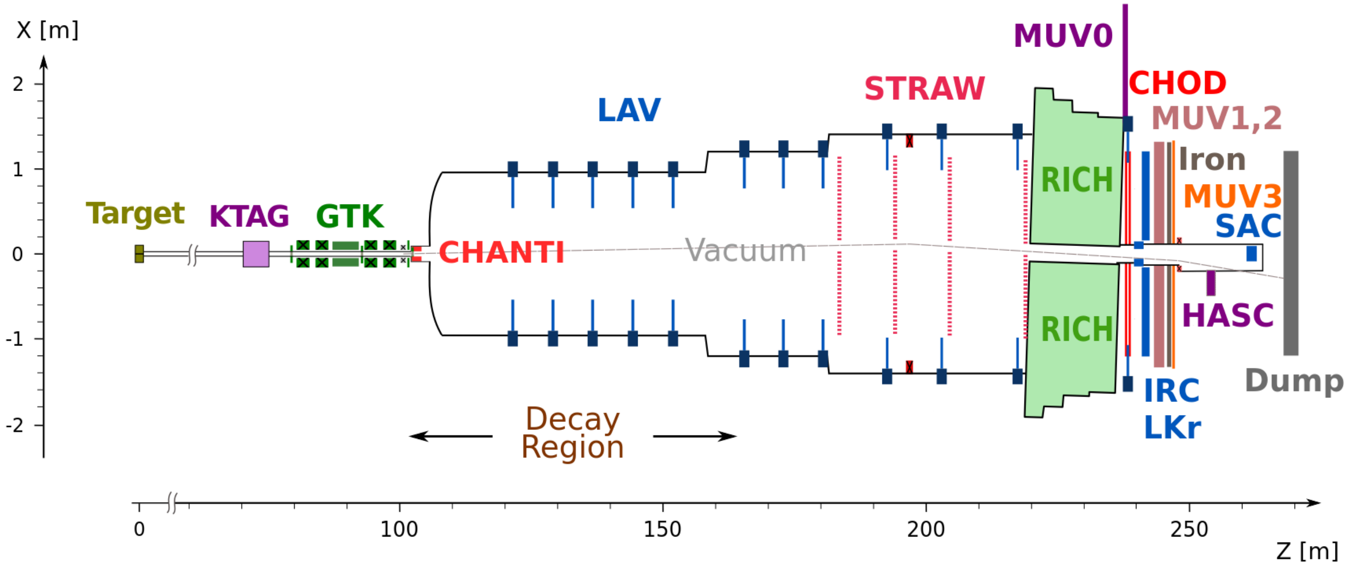
$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{stat} \pm 0.9_{syst}) \times 10^{-11} @ 68\%\ CL$$

Background-only hypothesis: $p = 3.4 \times 10^{-4}$ ⇒ significance = 3.4σ

RUN2 Upgrades



Improvements for RUN2



Background	N(exp) 2018 (S2)
Upstream	$2.76^{+0.90}_{-0.70}$
$K^+ \to \pi^+\pi^0$	0.52 ± 0.05
$K^+ \to \mu^+\nu$	0.45 ± 0.06
$K^+ \to \pi^+\pi^- e^+\nu$	0.41 ± 0.10
$K^+ \to \pi^+\pi^+\pi^-$	0.17 ± 0.08
Total	$4.31^{+0.91}_{-0.72}$

Largest backgrounds:

1. Upstream
2. Decay $K^+ \to \pi^+\pi^0$

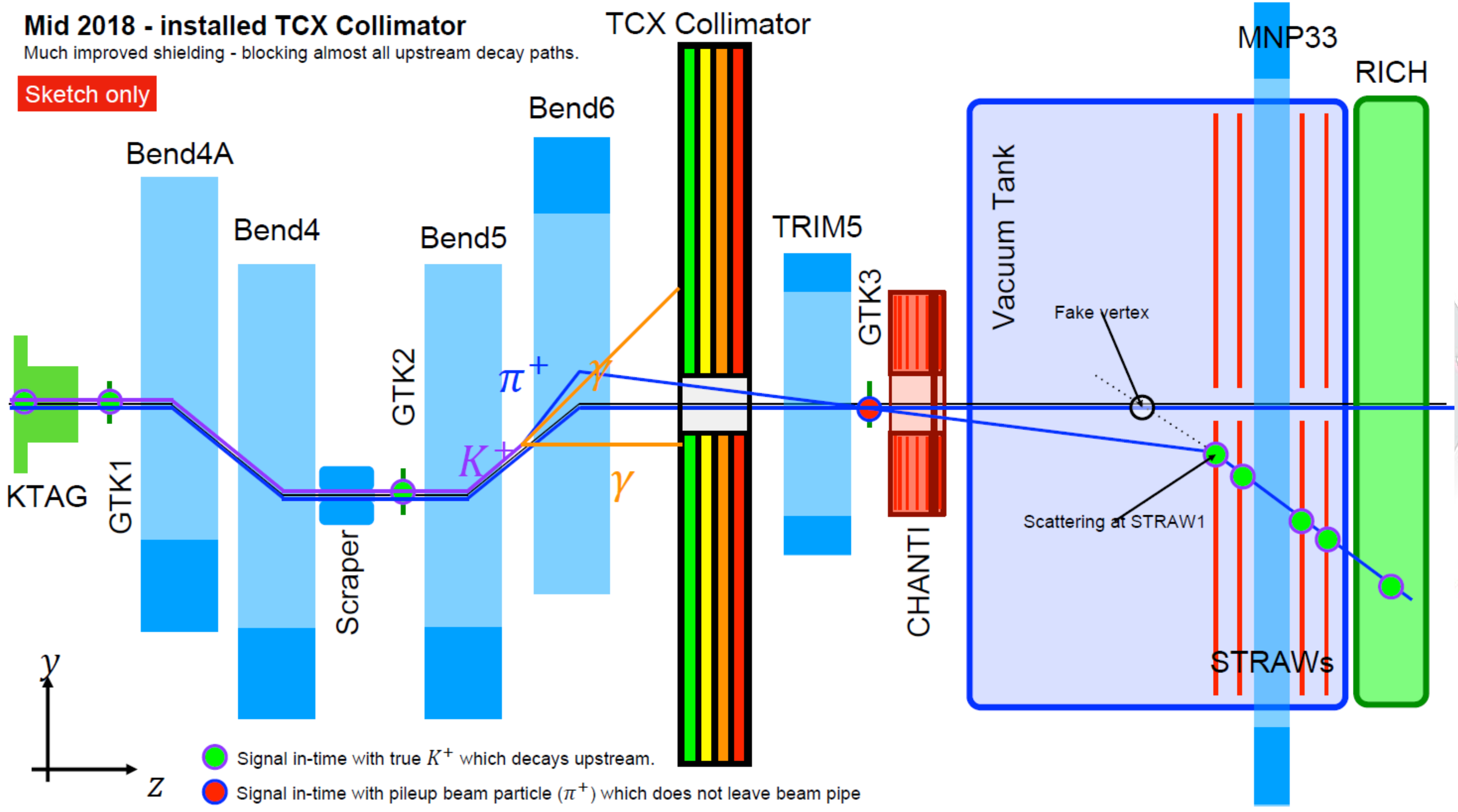
- **New GTK station:** GTK0
- **PID improved:** K^+ - KTAG, π^+ - RICH, Calorimeters (LKr, MUV1,2), MUV3 (μ-detector) ⟶ random veto and acceptance
- **New vetoes:** upstream (VetoCounter, ANTI0) and downstream HASC2
- **New collimator**
- **New L0 Trigger Processor:** L0TP+
- **New L1 trigger algorithms:** STRAW and LAV

⟹
- trigger efficiency
- Bandwidth exploitation

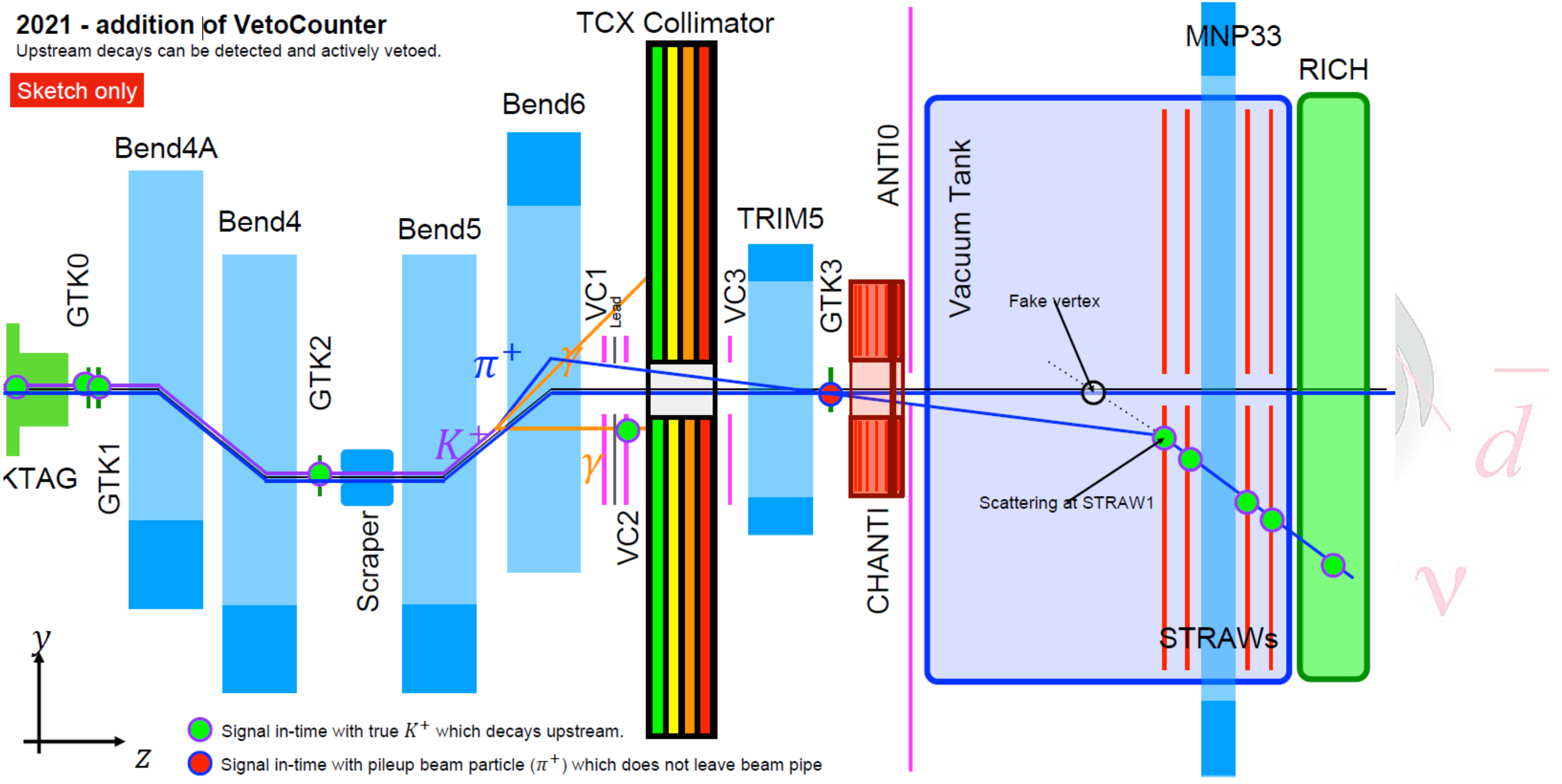
Then:

- **Intensity increased** by ~35% with respect to 2018 [450 → 600 MHz].
- Improvements to the **trigger configuration.**

new collimator



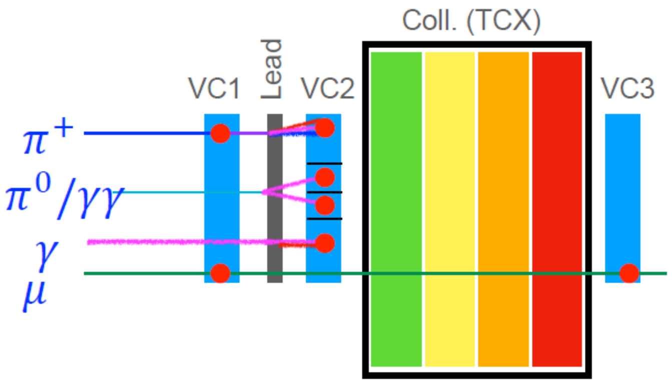
New Upstream Vetoes



New upstream vetos: VetoCounter & ANTI0

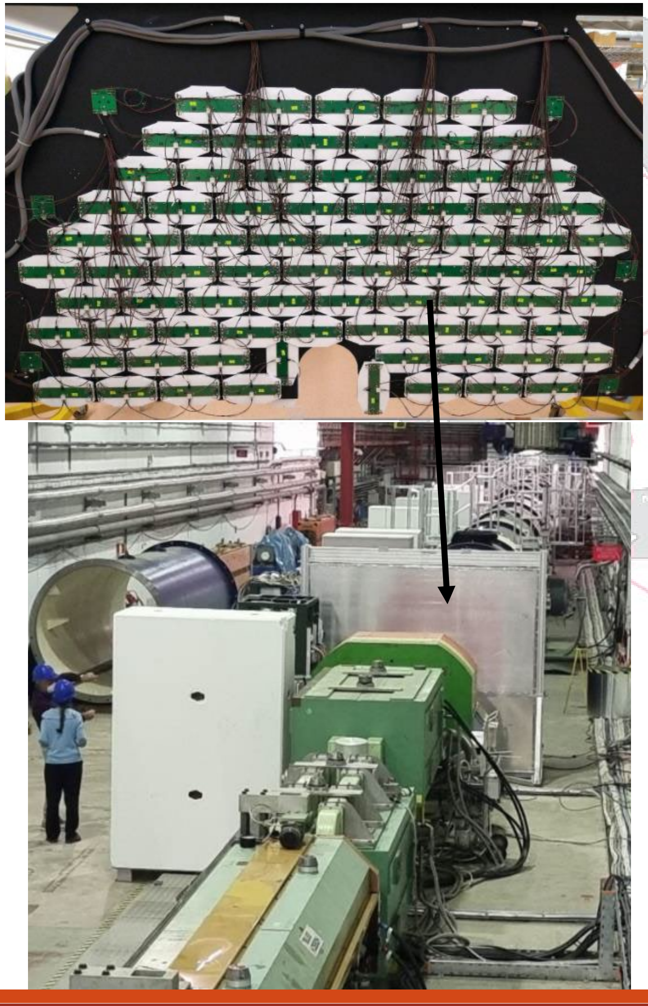
VetoCounter

- Detect particles from decays upstream of final collimator.
- Factor ~**3 rejection** with ~2% accidental veto.



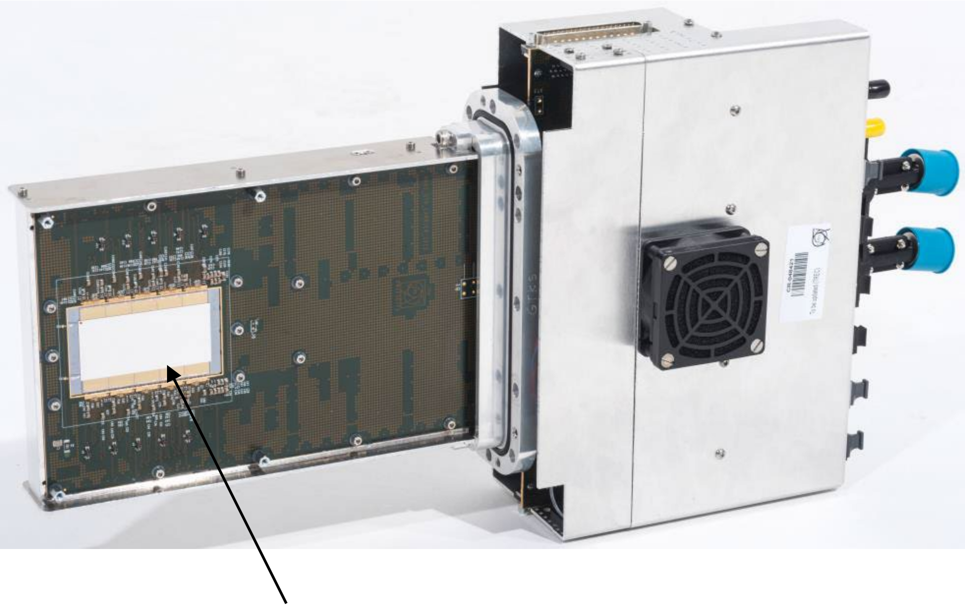
ANTI0

- Detect particles up to ~1 m from beam line.
- Reject ~20% of upstream background with <1% signal loss.

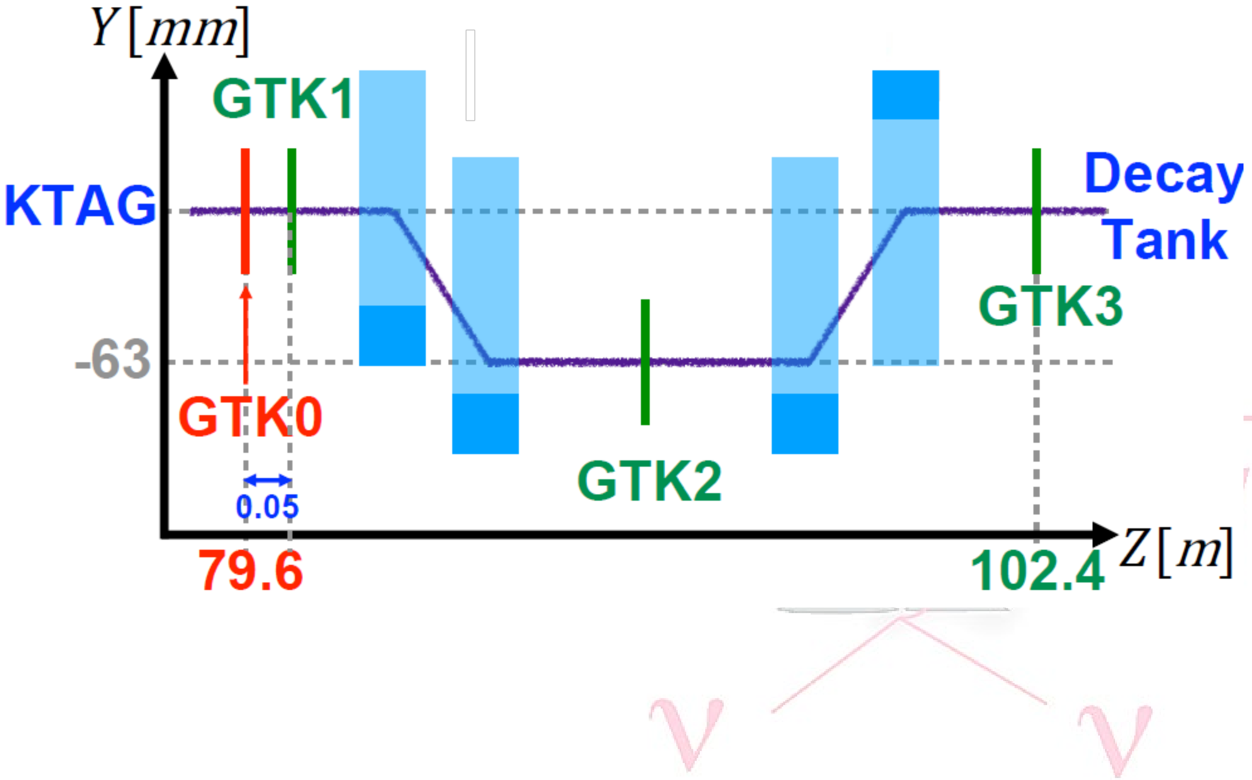


4^{th} GTK station

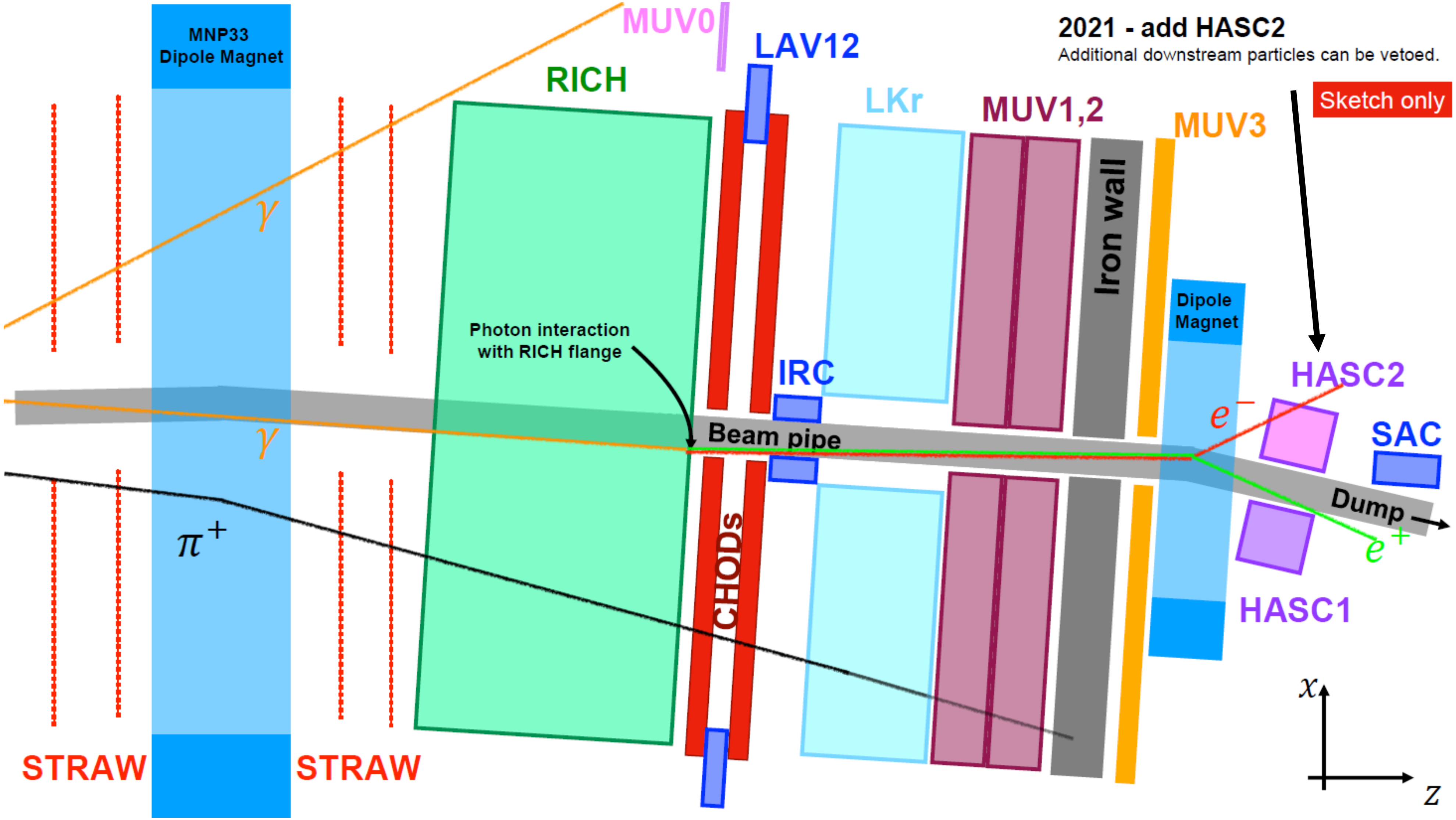
- Si Pixel detector exposed to ~1GHz beam.
- Essential for $K^+ - \pi^+$ matching.
- Measures K^+ 3-mom and time
- 4th GTK station improves efficiency and pileup resilience.



Si Pixels ~(30x60 mm active area)



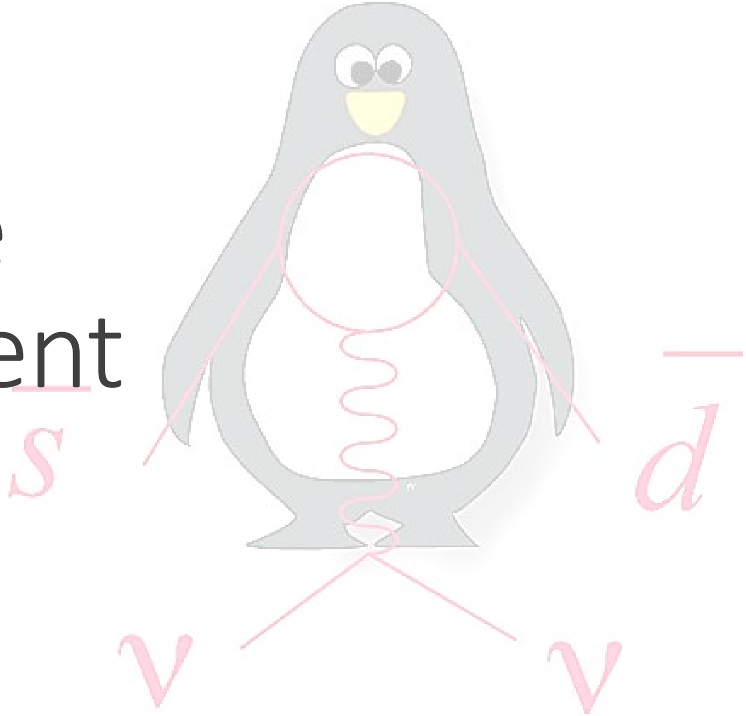
New donwstream Veto



Addition of HASC2:

- **30% less $K^+ \to \pi^+\pi^0$**
- 18% less $K^+ \to \pi^+\pi^+\pi^-$
- 3.5% less $K^+ \to \mu^+\nu$
- with only 1.5% signal loss

Last updates about the $K^+ \to \pi^+\upsilon\bar{\upsilon}$ measurement



Data 2021-22: single event sensitivity

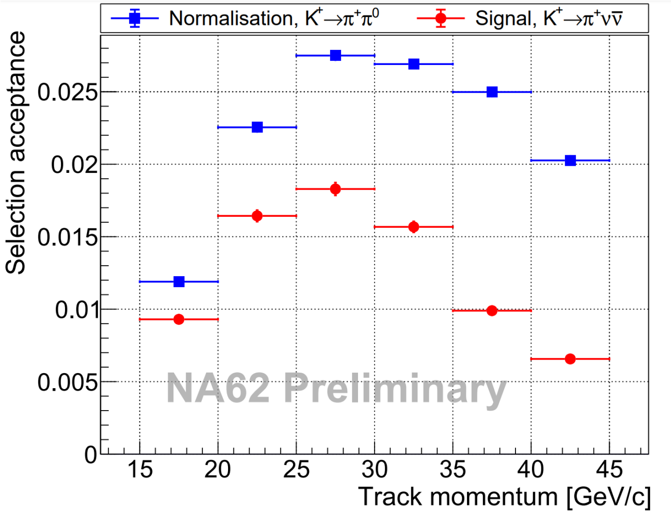
$$N_{\pi\nu\nu}^{SM,exp} = \frac{BR(\pi\nu\nu)_{SM}}{SES} = \frac{BR(\pi\nu\nu)_{SM}}{BR(\pi\pi)} \frac{A_{\pi\nu\nu}}{A_{\pi\pi}} (N_{\pi\pi} \times D_0)\, \varepsilon_{trig}\, \varepsilon_{RV}$$

$N_{\pi\pi}$	Normalisation $K^+ \to \pi^+\pi^0$	2.0×10^8
$A_{\pi\pi}$	Normalisation acceptance	$(13.410 \pm 0.005)\%$
N_K	Effective K^+ decays	2.9×10^{12}
$A_{\pi\nu\bar{\nu}}$	Signal acceptance	$(7.6 \pm 0.2)\%$
ε_{trig}	Trigger efficiency	$(85.9 \pm 1.4)\%$
ε_{RV}	Random veto efficiency	$(63.6 \pm 0.6)\%$
$\mathcal{B}_{SES}$	Single event sensitivity	$(0.84 \pm 0.03) \times 10^{-11}$

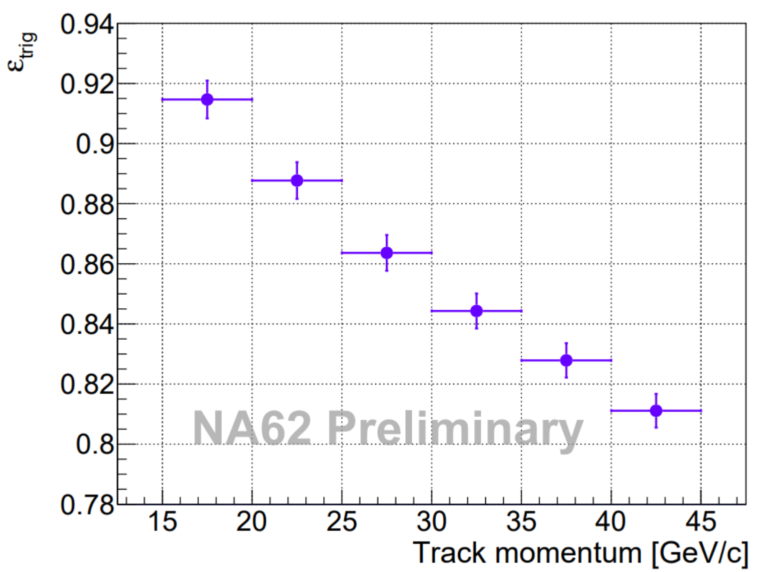
Assuming $\mathcal{B}_{\pi\nu\bar{\nu}}^{SM} = 8.4 \times 10^{-11}$:

2021–22: $N_{\pi\nu\bar{\nu}} = 10.00 \pm 0.34$

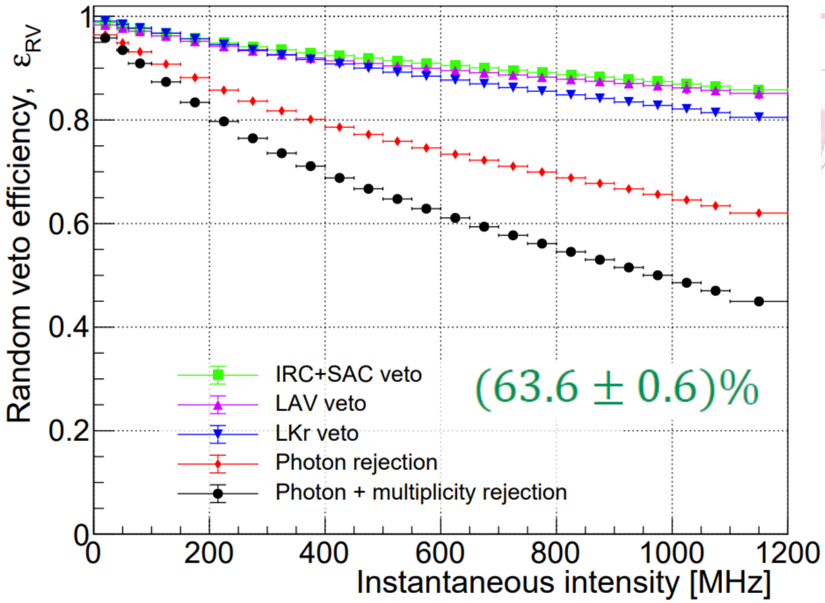
c.f. 2016–18 : $N_{\pi\nu\bar{\nu}} = 10.01 \pm 0.42$



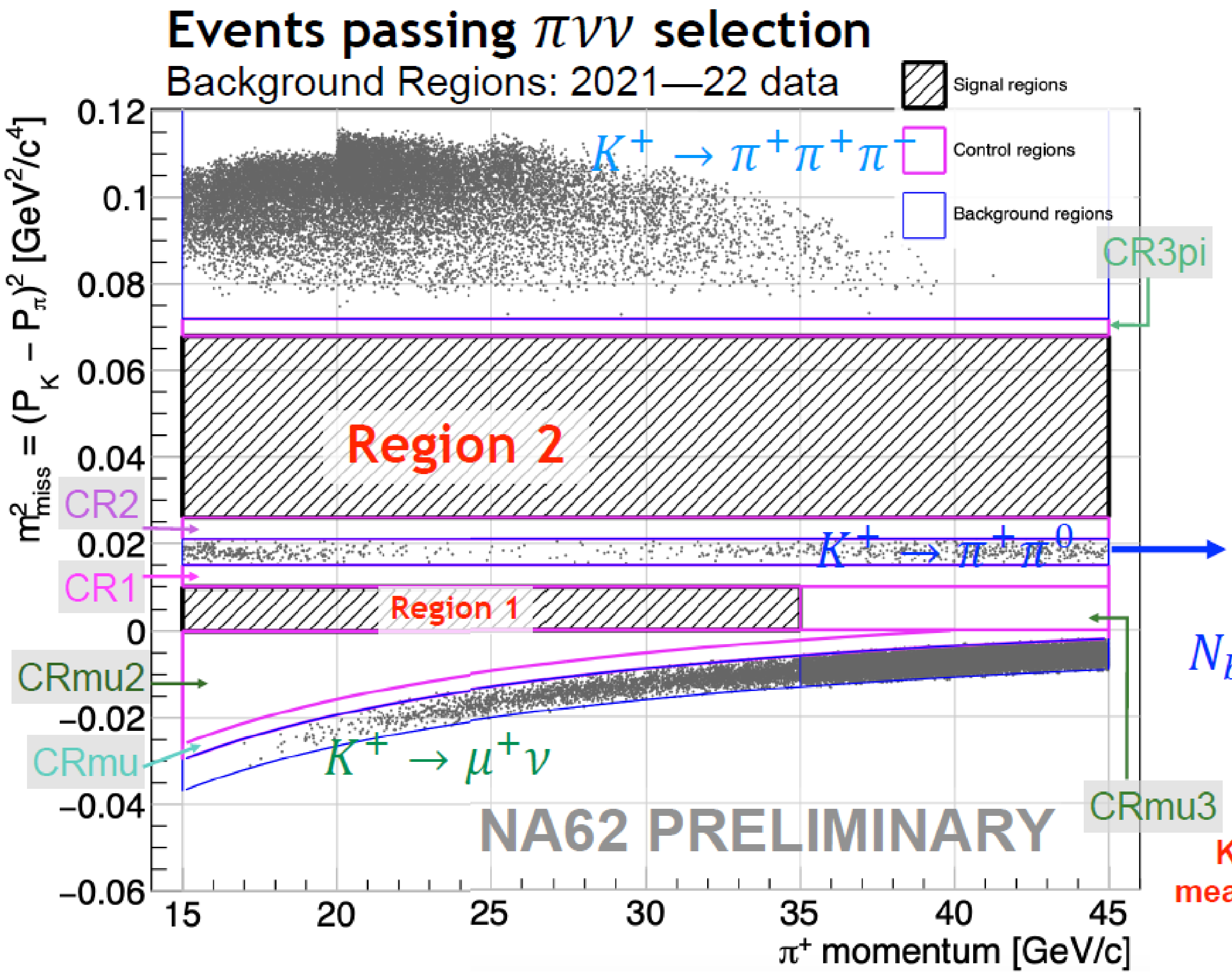
Case	OLD 2018 (S2)	NEW 2021-22	
Norm.	11.8%	13.4%	+15%
Signal	(6.37±0.64)%	(7.61±0.18)%	+20%



$\varepsilon_{trig}(new) = (85.9 \pm 1.4)\%$



Background regions



Backgrounds from kinematic misconstruction tails in m^2_{miss}

$$N_{bg} = N_{bkgR} \cdot f_{tail} = N_{bkgR} \cdot \frac{N^{CS}_{SR}}{N^{CS}_{bkgR}}$$

Number of events passing signal selection in background region

Control sample events in Signal Regions

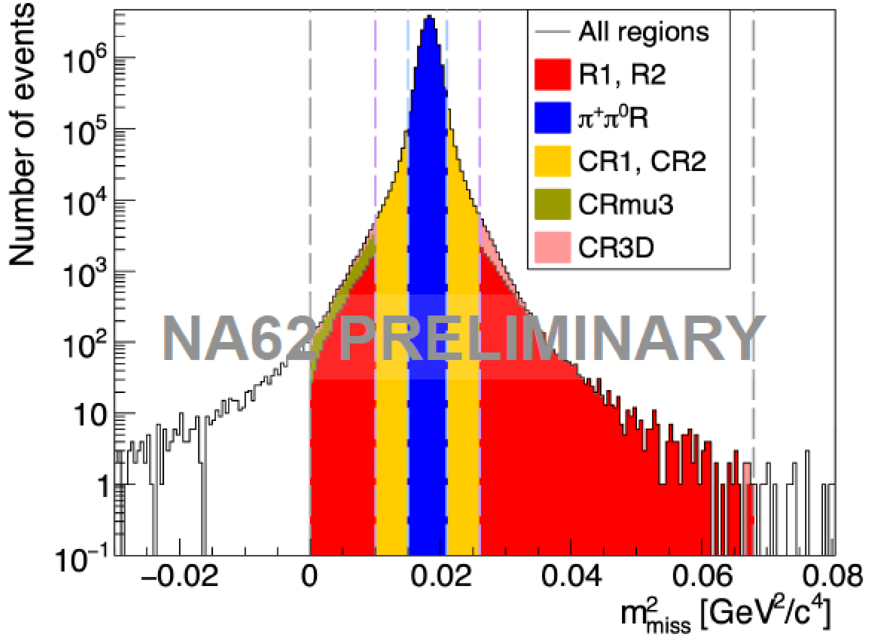
Kinematic tail fraction: measured in control sample

Control sample events in Background Region

Backgrounds from kinematic tails

$K^+ \to \pi^+\pi^0(\gamma)$

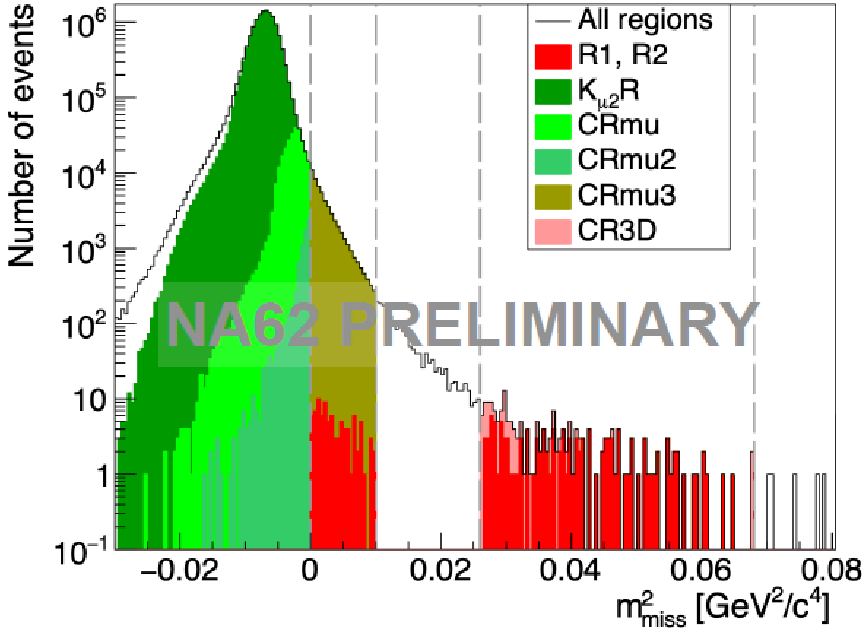
control sample of $K^+ \to \pi^+\pi^0$ events with $\pi^0 \to \gamma\gamma$ and 2 photons detected in LKr:



$$N_{bg}(K^+ \to \pi^+\pi^0(\gamma)) = 0.83 \pm 0.05$$

$K^+ \to \mu^+\nu$

control sample of $K^+ \to \mu^+\nu$ events with RICH PID=π^+ and Calo PID=μ^+:



- <1% contribution from $K^+ \to \mu^+\nu$ followed by $\mu^+ \to e^+\nu\nu$

$$N_{bg}(K^+ \to \mu^+\nu) = 0.9 \pm 0.2$$

$K^+ \to \pi^+\pi^+\pi^-$

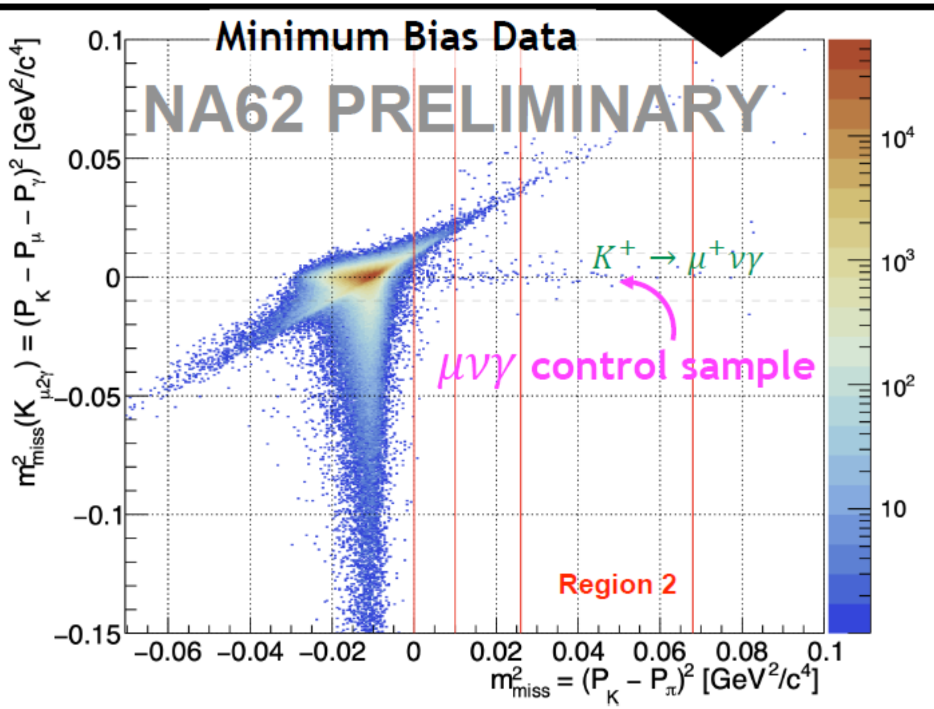
- Use MC to measure f_{tail}:

$$N_{bg}(K^+ \to \pi^+\pi^+\pi^-) = 0.11 \pm 0.03$$

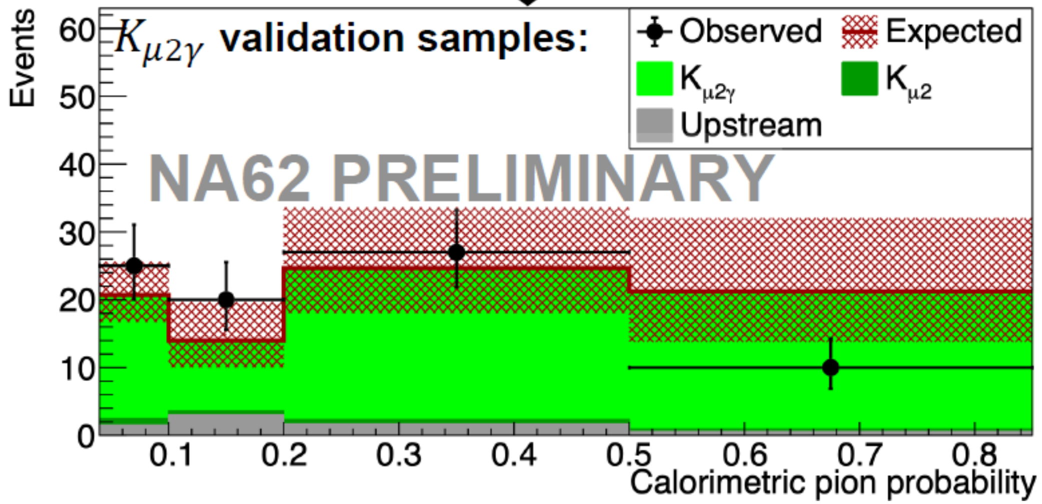
$K^+ \to \mu^+\nu\gamma$ background

- Kinematically select $K^+ \to \mu^+\nu\gamma$ events: $m^2_{miss}(K_{\mu 2\gamma}) = (P_K - P_\mu - P_\gamma)^2$
  - P_K : 4-momentum of K^+ from GTK (as normal)
  - P_μ : 4-momentum of track with μ^+ mass hypothesis.
  - P_γ : reconstructed from energy and position of LKr cluster (and position of K^+-μ^+ vertex).

Evaluate background expectation using $\mu\nu\gamma$ control sample from MinimumBias trigger, not applying Calorimetric BDT classifier and MUV3 signal:



Validation: data sample with PID = "less pion-like" (Calo BDT bins below π^+ bin).



- Before $K^+ \to \mu^+\nu\gamma$ veto: found excess of events at $p > 35\,GeV/c$ in Region 2 relative to 2016–18 data.
- Additional background identified and studied in data control samples & MC.
- $K^+ \to \mu^+\nu\gamma$ veto added to selection criteria for final analysis.

Upstream background evaluation

$$N_{bg} = \sum_i N_i f_{cda} P_i^{match}$$

N	Upstream Reference Sample: signal selection but invert CDA cut (CDA>4mm)
f_{cda}	Scaling factor : bad cda —> good cda
P_{match}	Probability to pass $K+ - \pi+$ matching

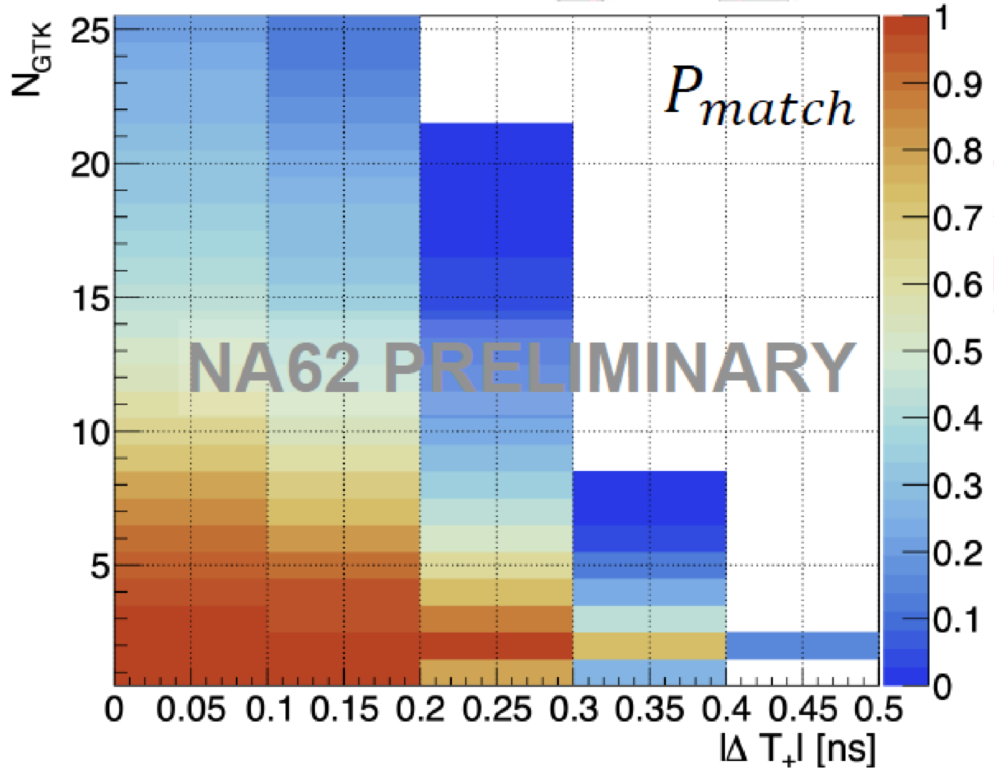
Calculate using bins (i) of $(\Delta T_{+}, N_{GTK})$

[Updated to fully data-driven procedure]

$N = 51 \quad f_{CDA} = 0.20 \pm 0.03 \quad < P_{match} > = 73\%$

$$N_{bg}(Upstream) = 7.4^{+2.1}_{-1.8}$$

- **Upstream reference sample contains all known upstream mechanisms.**
- N provides normalisation.
- f_{CDA} **depends only on geometry.**
- P_{match} **depends on** $(\Delta T_{+}, N_{GTK})$.



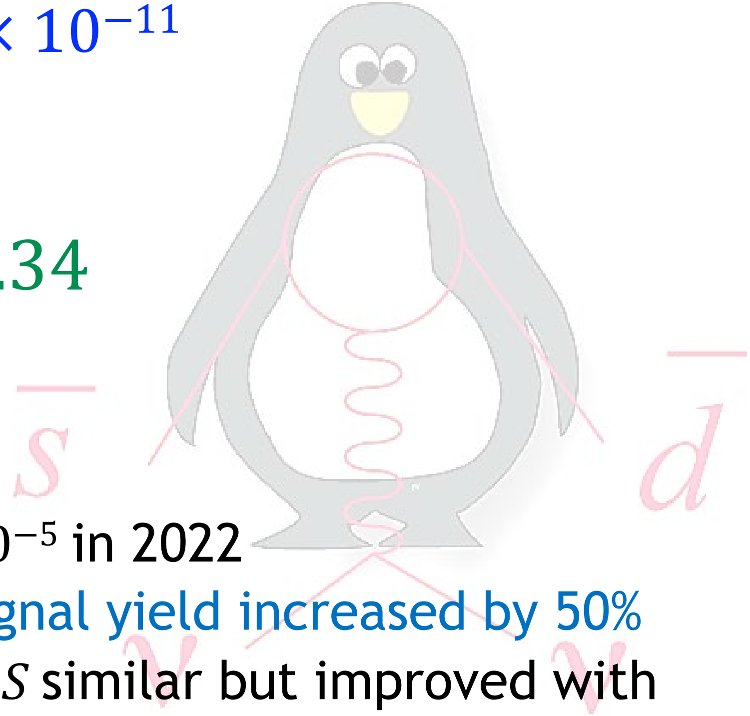
Summary of expectation

Backgrounds

$K^+ \to \pi^+\pi^0(\gamma)$	0.83 ± 0.05
$K^+ \to \pi^+\pi^0$	0.76 ± 0.04
$K^+ \to \pi^+\pi^0\gamma$	0.07 ± 0.01
$K^+ \to \mu^+\nu(\gamma)$	1.70 ± 0.47
$K^+ \to \mu^+\nu$	0.87 ± 0.19
$K^+ \to \mu^+\nu\gamma$	0.82 ± 0.43
$K^+ \to \pi^+\pi^+\pi^-$	0.11 ± 0.03
$K^+ \to \pi^+\pi^-e^+\nu$	$0.89^{+0.34}_{-0.28}$
$K^+ \to \pi^0\ell^+\nu$	< 0.001
$K^+ \to \pi^+\gamma\gamma$	0.01 ± 0.01
Upstream	$7.4^{+2.1}_{-1.8}$
Total	$11.0^{+2.1}_{-1.9}$

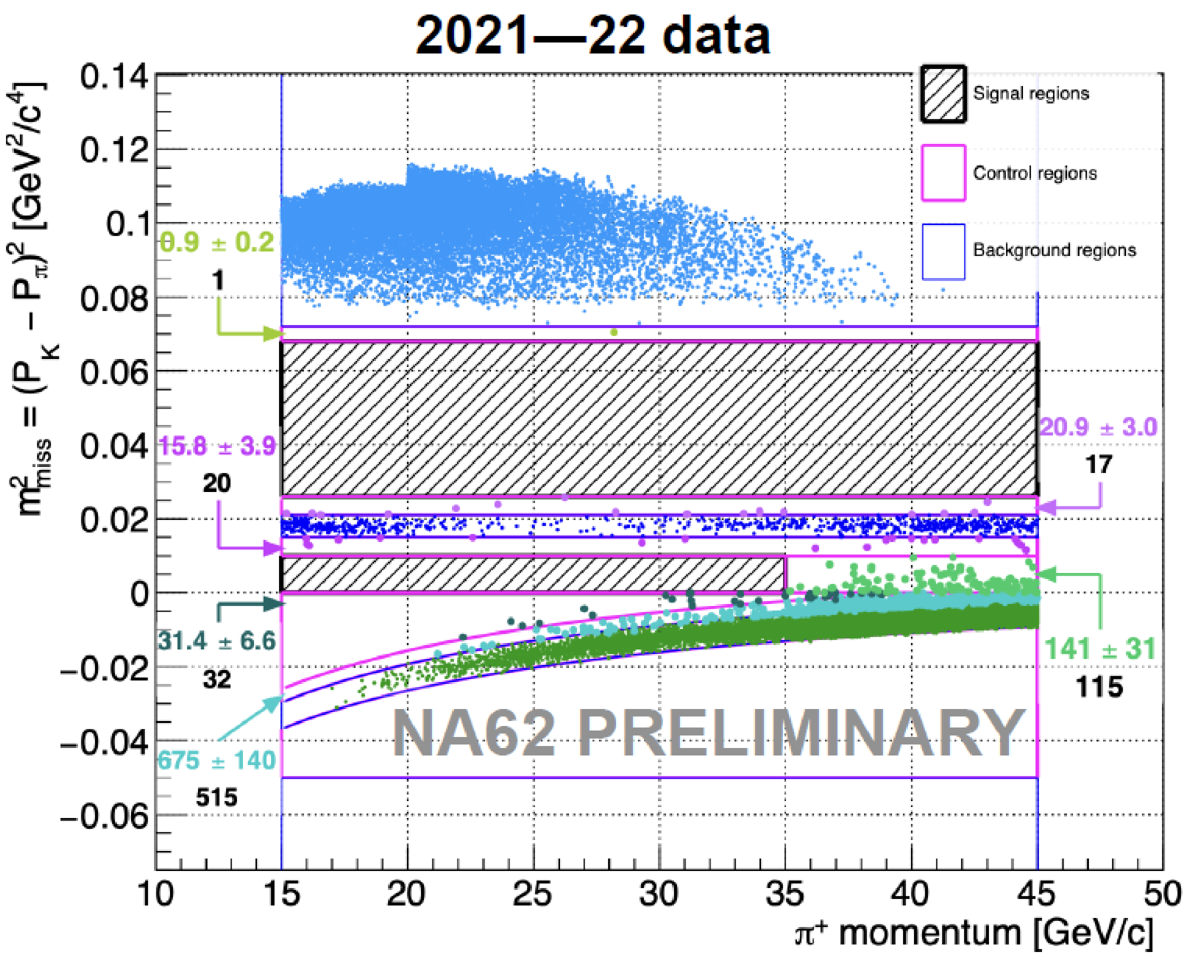
$$\mathcal{B}_{SES} = (0.84 \pm 0.03) \times 10^{-11}$$

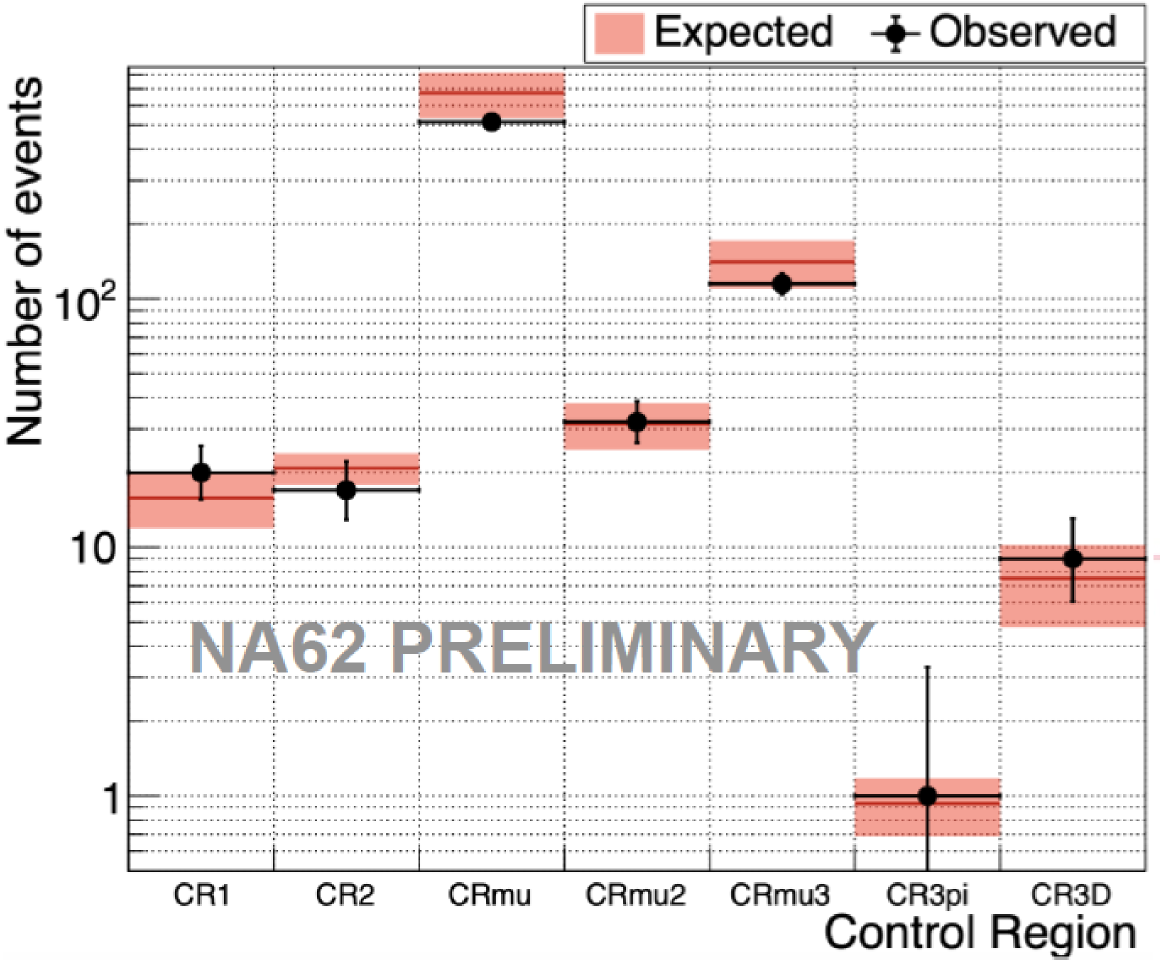
$$N_{\pi\nu\nu} = 10.00 \pm 0.34$$



- $N^{SM}_{\pi\nu\bar{\nu}}$ per SPS burst: 2.5×10^{-5} in 2022
- c.f. 1.7×10^{-5} in 2018. $\Rightarrow$ signal yield increased by 50%
- Sensitivity for BR $\sim \sqrt{S+B}/S$ similar but improved with respect to 2018 analysis, for same amount of data

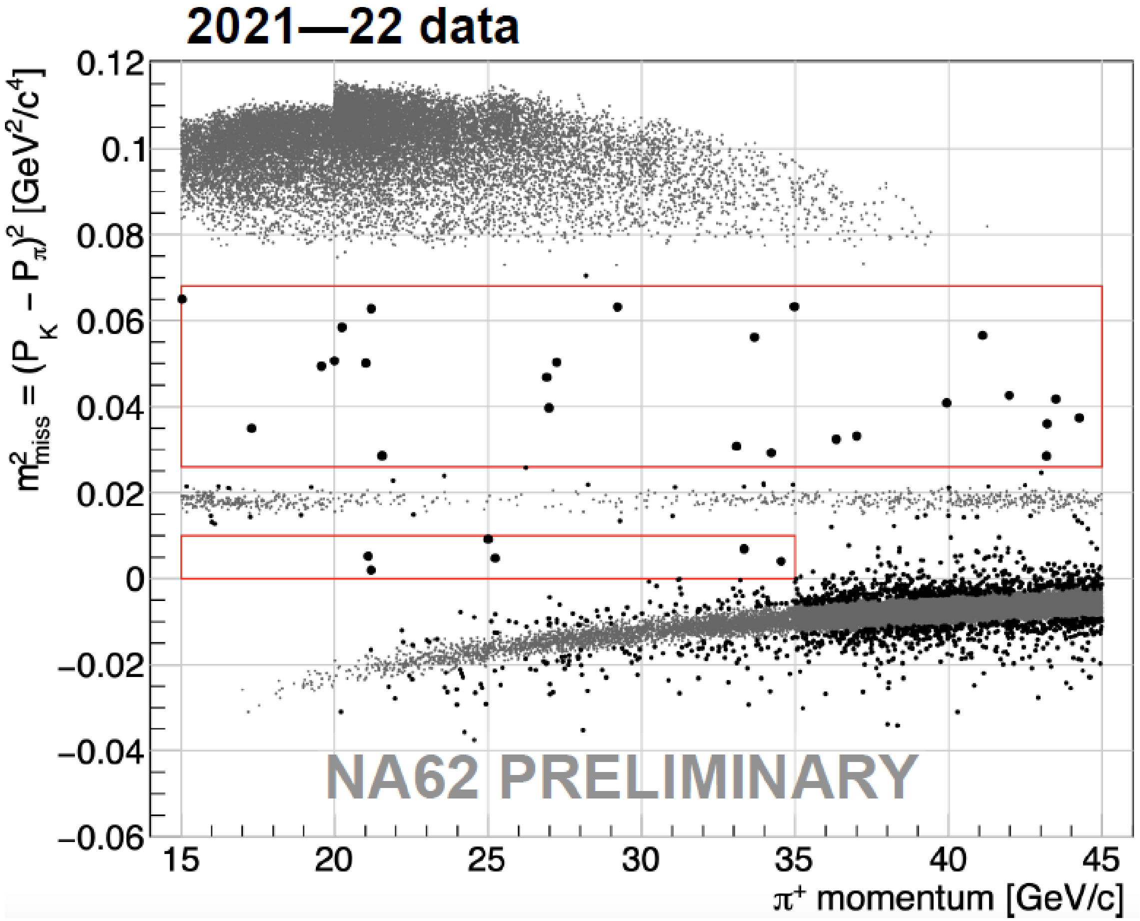
Control regions



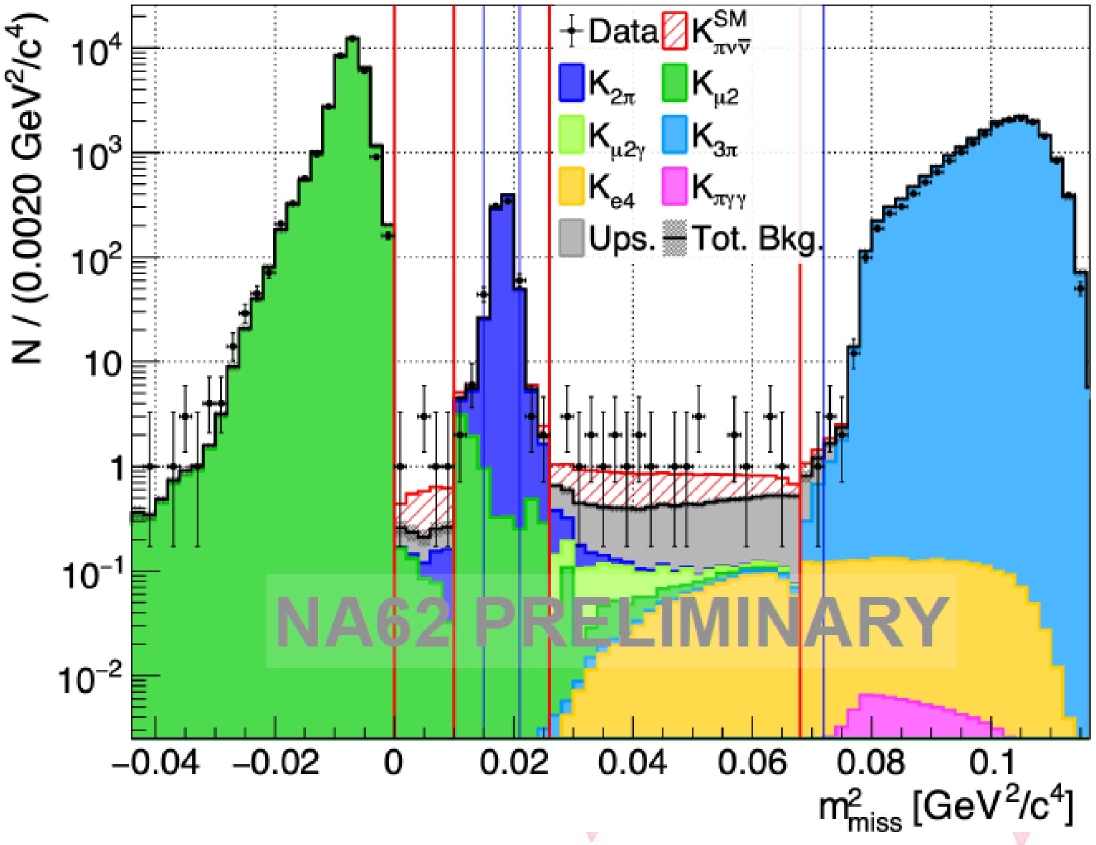


Good agreement in control regions validates background expectations

Result: events observed



1D projection with differential background predictions and SM signal expectation [not a fit]:

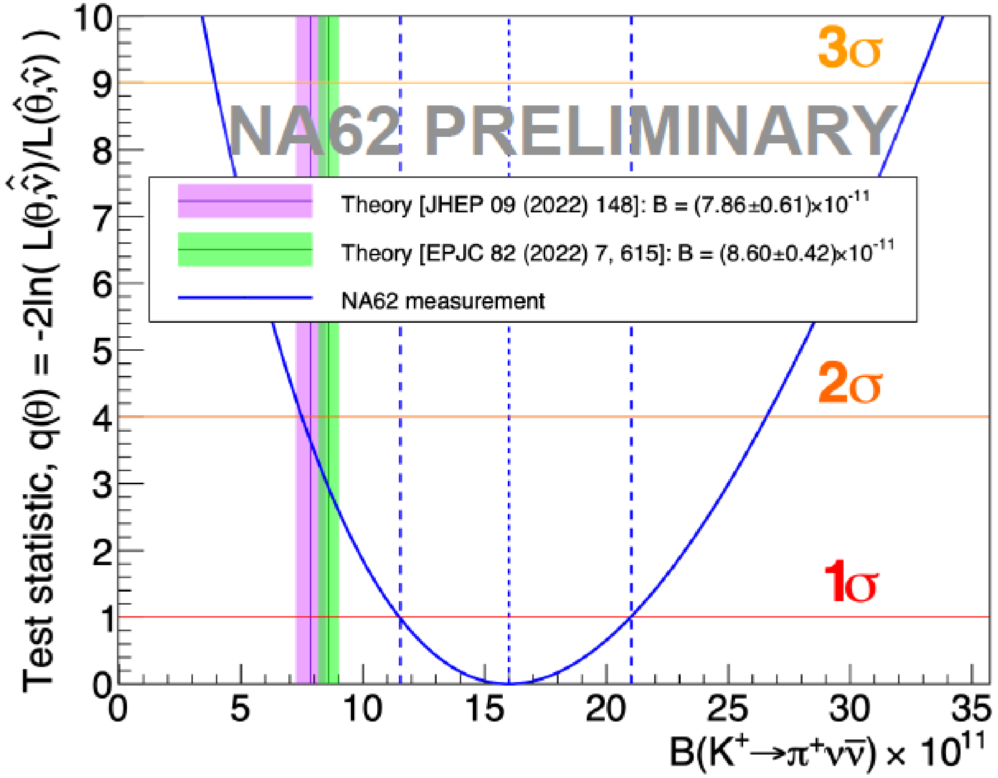


Expected SM signal $N^{SM}_{\pi\nu\bar{\nu}} = 10.00 \pm 0.34$
Expected background: $N_{bg} = 11.0^{+2.1}_{-1.9}$

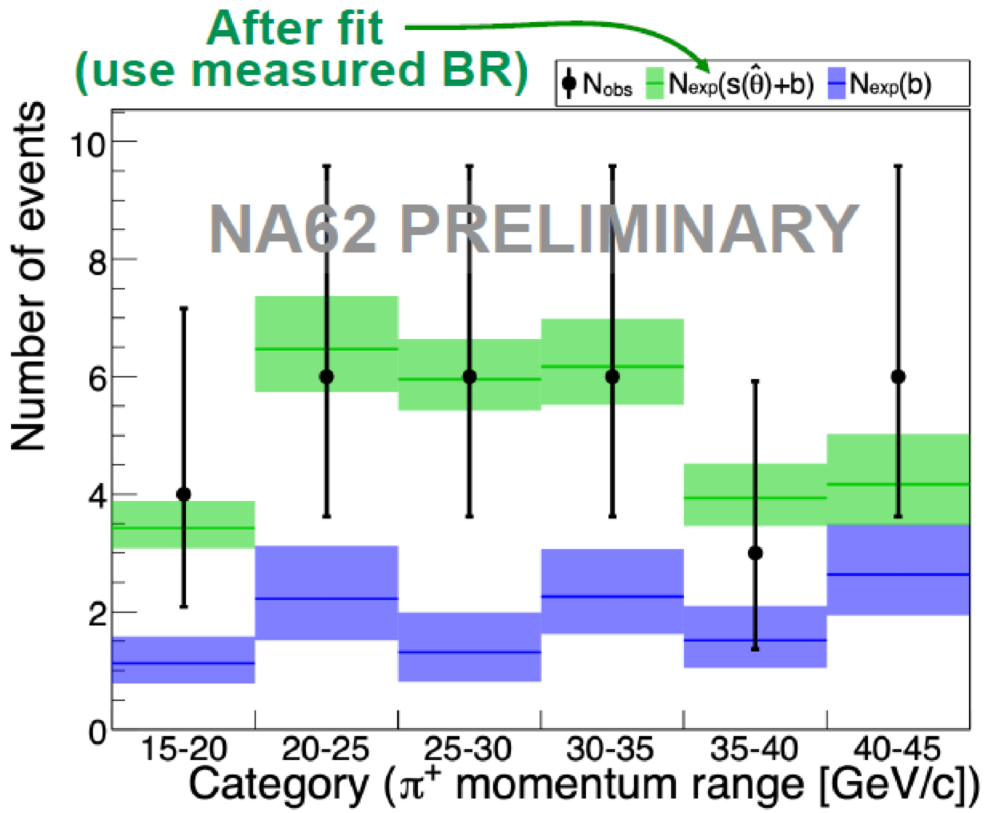
Observed: N_{obs} = 31

Result: 2021-22 Data

Measure $\mathcal{B}_{\pi\nu\nu}$ and 68% (1σ) confidence interval using a profile likelihood ratio test statistic $q(\theta)$



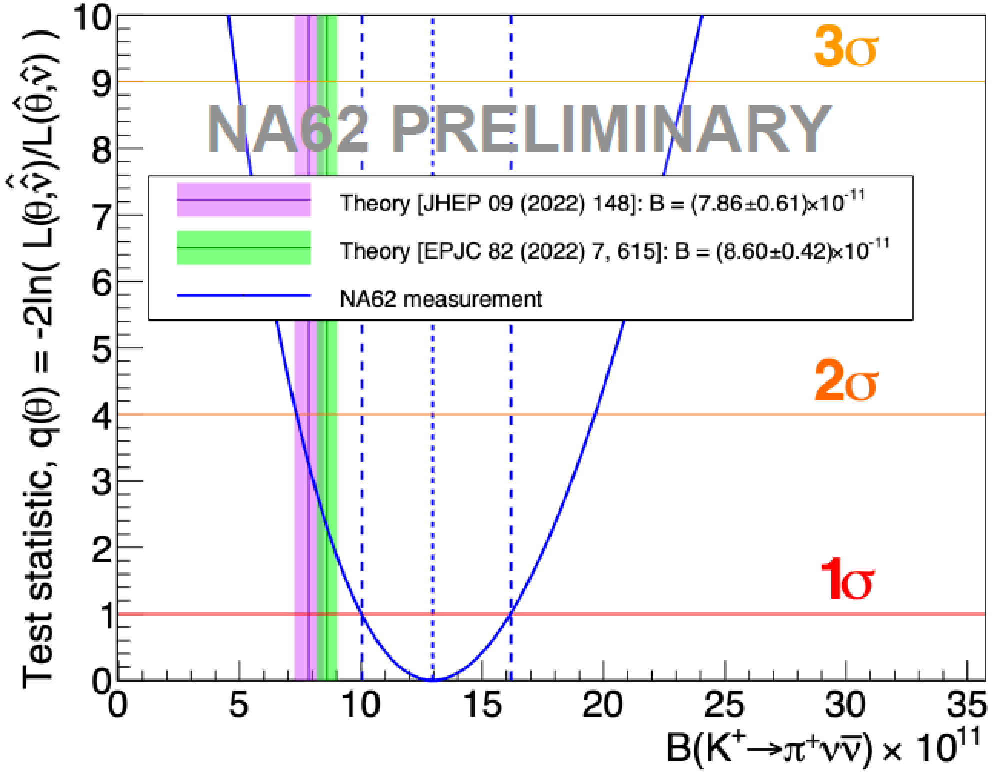
6 (momentum bin) categories

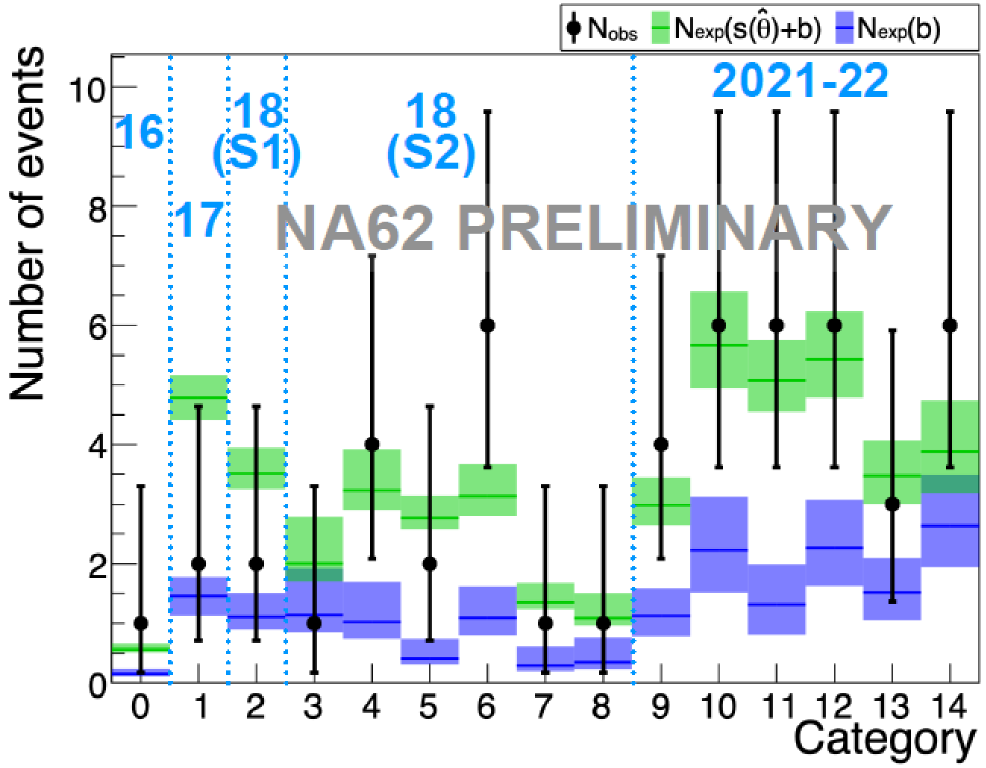


$$\mathcal{B}_{21-22}(K^+ \to \pi^+ \nu\bar{\nu}) = \left(16.0^{+5.0}_{-4.5}\right) \times 10^{-11} = \left(16.0\ (^{+4.8}_{-4.2})_{stat}\ (^{+1.4}_{-1.3})_{syst}\right) \times 10^{-11}$$

Combining NA62 results: 2016-22

Integrating 2016—22 data: $N_{bg} = 18^{+3}_{-2}$, $N_{obs} = 51$



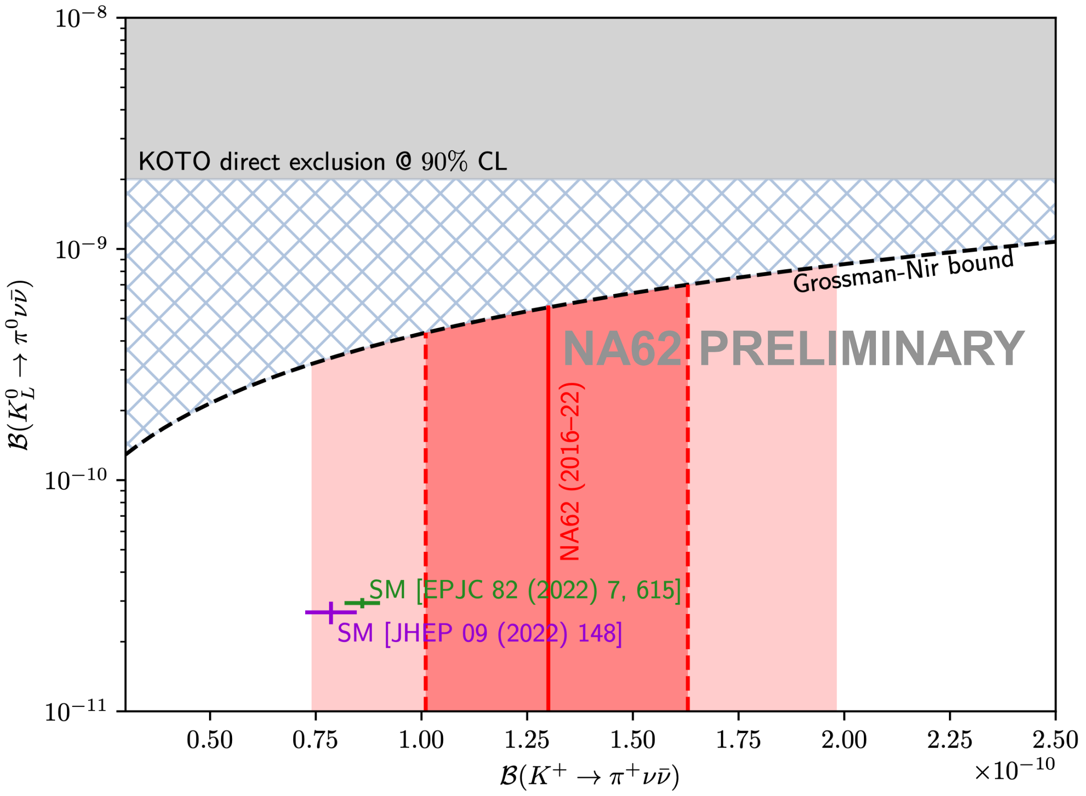


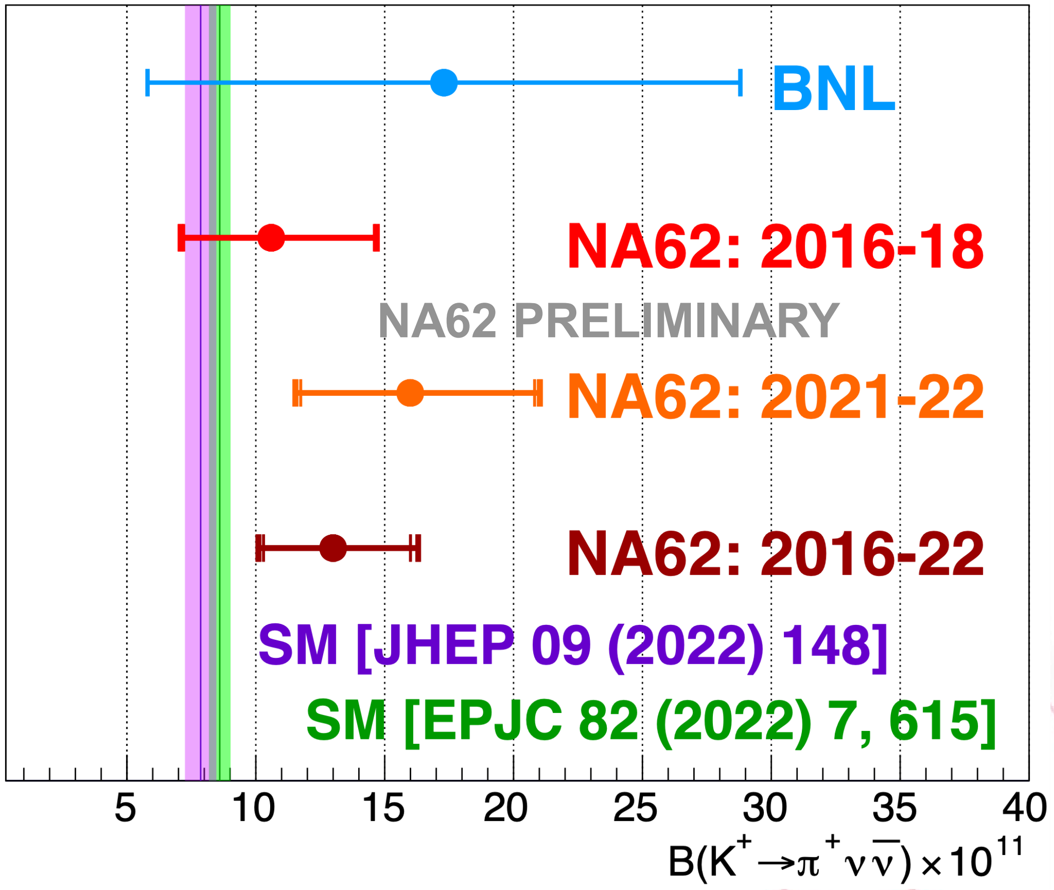
$$\mathcal{B}_{16-22}(K^+ \to \pi^+ \nu\bar{\nu}) = (13.0^{+3.3}_{-2.9}) \times 10^{-11} = (13.0\ (^{+3.0}_{-2.7})_{stat}\ (^{+1.3}_{-1.2})_{syst}) \times 10^{-11}$$

Background-only hypothesis p-value = 2×10^{-7} ⇒ significance $Z > 5$

Results in context

- NA62 results are consistent
- Central value moved up (now 1.5—1.7σ above SM)
- Fractional uncertainty decreased: from 40% to 25%
- Bkg-only hypothesis rejected with significance Z>5
- First observation of $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ decay



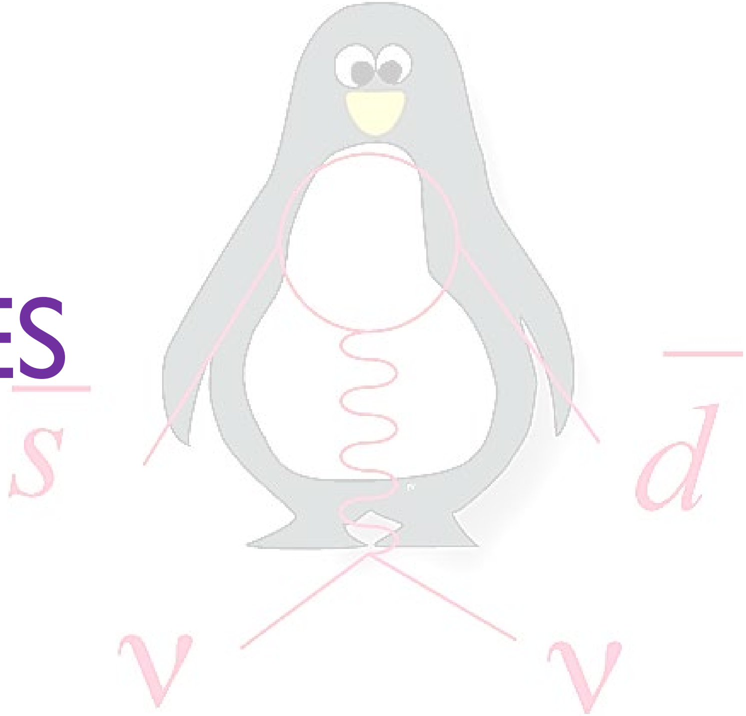


$$\mathcal{B}^{16-22}_{\pi\nu\bar{\nu}} = (13.0^{+3.3}_{-2.9}) \times 10^{-11}$$

Need full NA62 data-set to clarify SM agreement or tension

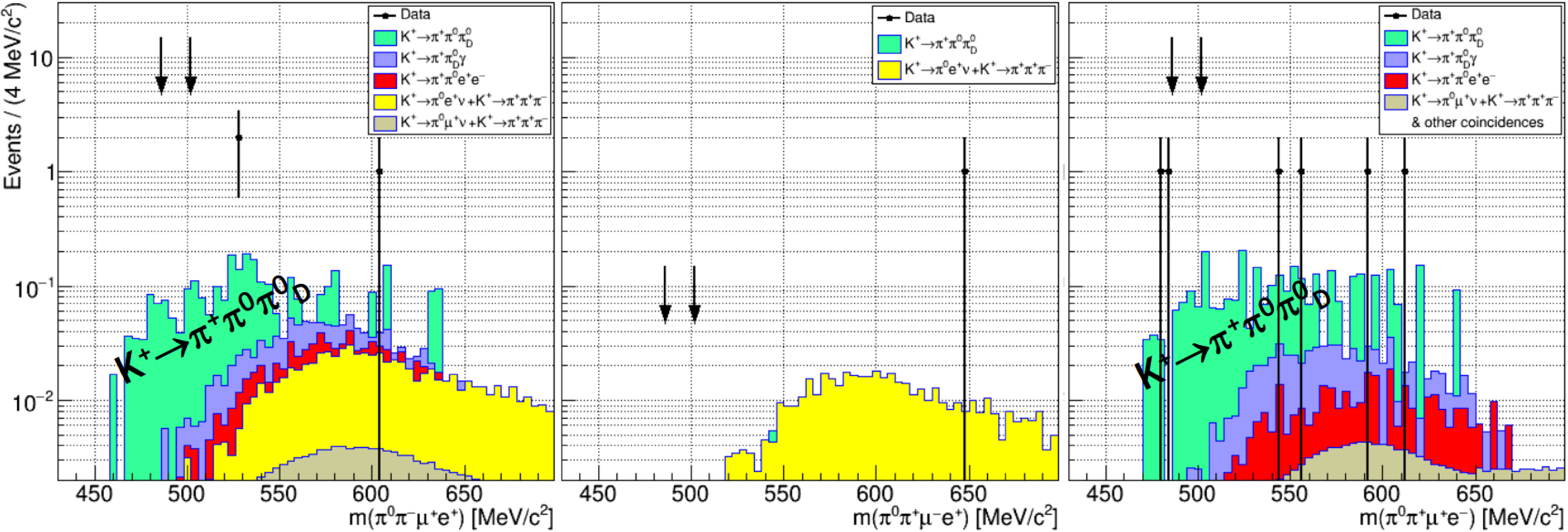
2023—LS3 data-set collection & analysis in progress...

LNV / LFV SEARCHES



First search for $K^+ \to \pi^0 \mu e$

[j.physletb.2024.239122]



$BR(K^+ \to \pi^0\pi^-\mu^+e^+) < 2.9 \times 10^{-10}$

$BR(K^+ \to \pi^0\pi^+\mu^-e^+) < 3.1 \times 10^{-10}$

$BR(K^+ \to \pi^0\pi^+\mu^+e^-) < 5.0 \times 10^{-10}$

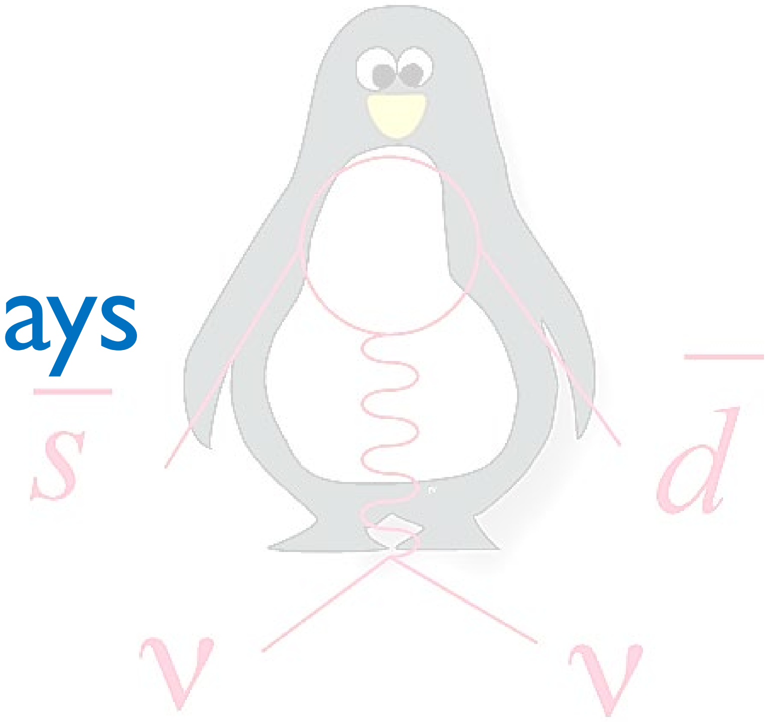
ULs at 90% CL

Other results from RUN1

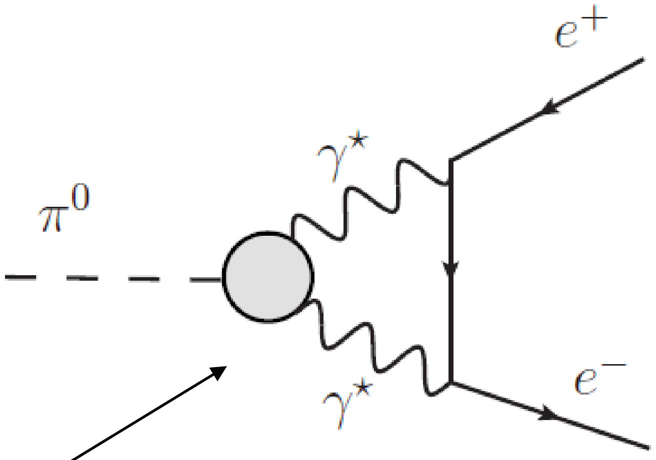
	Previous UL PDG 2019	NA62 UL at 90% CL	
$K^+ \to \pi^- \mu^+ e^+$	BR < 5.0 × 10^{-10}	BR < 4.2 × 10^{-11}	PRL 127 (2021) 131802
$K^+ \to \pi^+ \mu^- e^+$	BR < 5.2 × 10^{-10}	BR < 6.6 × 10^{-11}	PRL 127 (2021) 131802
$\pi^0 \to \mu^- e^+$	BR < 3.4 × 10^{-9}	BR < 3.2 × 10^{-10}	PRL 127 (2021) 131802
$K^+ \to \pi^- \mu^+ \mu^+$	BR < 8.6 × 10^{-11}	BR < 4.2 × 10^{-11} (25% of dataset)	PLB 797 (2019) 134794
$K^+ \to \pi^- e^+ e^+$	BR < 6.4 × 10^{-10}	BR < 5.3 × 10^{-11}	PLB 830 (2022) 137172
$K^+ \to \pi^- \pi^0 e^+ e^+$	N/A	BR < 8.5 × 10^{-10}	PLB 830 (2022) 137172
$K^+ \to \mu^- \nu e^+ e^+$	N/A	BR < 8.1 × 10^{-11}	PLB 838 (2023) 137679

With the RUN2 data NA62 can improve ULs on LFV / LNV kaon decays by more than one order of magnitude

Rare Kaon and Pion Decays



$\pi^0 \to e^+e^-$: Overview



- Experimentally observable:

$$\mathrm{BR}(\pi^0 \to e^+e^-(\gamma), X > X_{cut}), \quad X = m_{ee}^2/m_{\pi^0}^2$$

  - Dalitz decay $\pi^0 \to \gamma e^+e^-$ dominant in low-x region
  - For $x > x_{cut} = 0.95$, Dalitz decay ≈ 3.3% of $\mathrm{BR}(\pi^0 \to e^+e^-(\gamma))$
- Previous best measurement by KTeV [Phys.Rev.D 75 (2007) 012004]:

$$\mathrm{BR}(\pi^0 \to e^+e^-(\gamma), X > 0.95) = (6.44 \pm 0.25 \pm 0.22) \times 10^{-8}$$

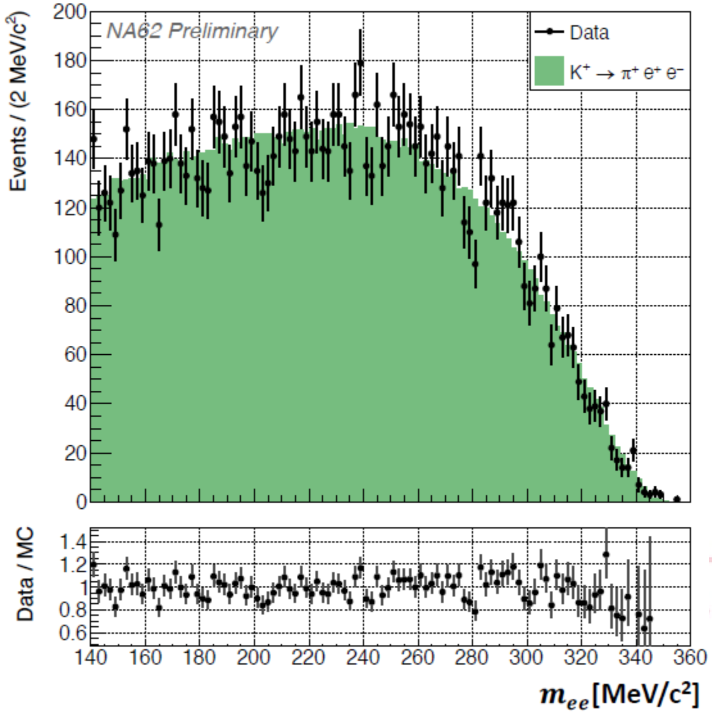
- Diagram considered in theoretical predictions leading to $\mathrm{BR}(\pi^0 \to e^+e^-(\gamma), \text{no-rad})$ for various $\pi^0 \to \gamma^*\gamma^*$ transition form factors.

Using latest radiative corrections in [JHEP 10 (2011) 122], [Eur.Phys.J.C 74 (2014) 8, 3010], the result can be extrapolated and compared with theory:

	$\mathcal{B}(\pi^0 \to e^+e^-, \text{no-rad}) \times 10^8$
KTeV, PRD 75 (2007)	6.84(35)
Knecht et al., PRL 83 (1999)	6.2(3)
Dorokhov and Ivanov, PRD 75 (2007)	6.23(9)
Husek and Leupold, EPJC 75 (2015)	6.12(6)
Hoferichter et al., PRL 128 (2022)	6.25(3)

$\pi^0 \to e^+e^-$: Data sample

- Data sample collected by NA62 in 2017 and 2018
- Signal decay mode: $K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^- \equiv K^+ \to \pi^+\pi^0_{ee}$
- Latest rediative corrections included in the simulation
- Normalization decay mode: $K^+ \to \pi^+e^+e^-$
  - identical final state
  - cancellation of systematics
- Multi-track electron trigger line used to collect both $K^+ \to \pi^+\pi^0_{ee}$ and $K^+ \to \pi^+e^+e^-$



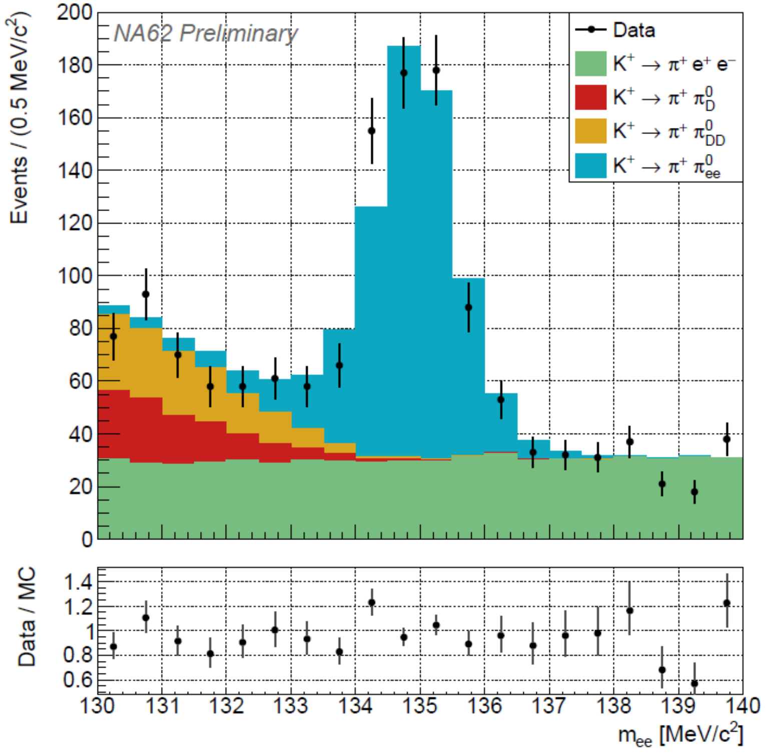
Backgrounds:

- $K^+ \to \pi^+e^+e^-$ ⟹ irreducible, flat in the signal region close to the π^0 mass
- $K^+ \to \pi^+\pi^0, \pi^0 \to \gamma e^+e^- \equiv K^+ \to \pi^+\pi^0_D$ ⟹
  - π^0 Dalitz decay distribution large-x tail
  - Photon conversion in STRAW + selection of a $e^\pm$ track from conversion
- $K^+ \to \pi^+\pi^0, \pi^0 \to e^+e^-e^+e^- \equiv K^+ \to \pi^+\pi^0_{DD}$ ⟹ π^0 double Dalitz decay with two undetected $e^\pm$

$\pi^0 \to e^+e^-$: result

- Fit region for signal extraction in $m_{ee} \in (130,140)$ MeV/c^2
- 597 ± 29 signal events
- The results are compatible with the previous measurement and the theoretical predictions:

$$\mathcal{B}(\pi^0 \to e^+e^-(\gamma), x > 0.95) = (5.86 \pm 0.30_{stat} \pm 0.11_{syst.} \pm 0.19_{ext.})\times 10^{-8}$$
$$= (5.86 \pm 0.37)\times 10^{-8}$$

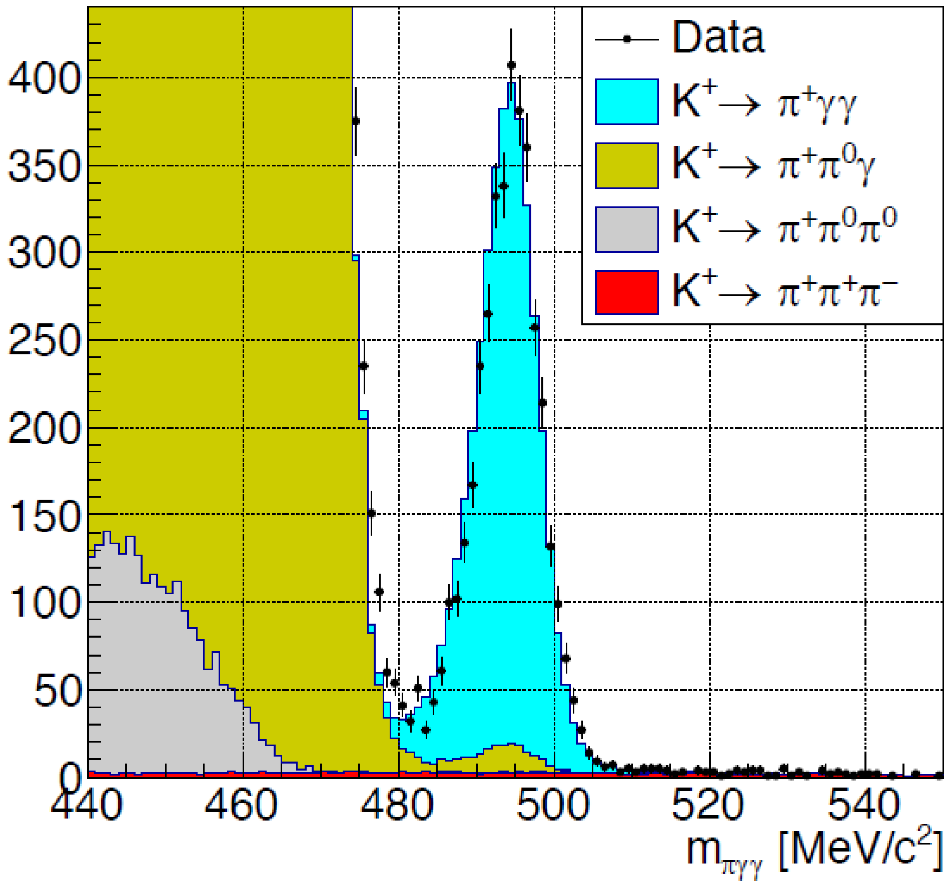


	$\delta\mathcal{B}[10^{-8}]$	$\delta\mathcal{B}/\mathcal{B}[\%]$
Statistical uncertainty	0.30	5.1
Trigger efficiency	0.07	1.2
Radiative corrections for $\pi^0 \to e^+e^-$	0.05	0.9
Background	0.04	0.7
Reconstruction and particle-ID	0.04	0.7
Beam simulation	0.03	0.5
Total systematic uncertainty	0.11	1.9
Total external uncertainty	0.19	3.2

$K^+ \to \pi^+\gamma\gamma$: overview

[j.physletb.2024.138513]

- Crucial test of Chiral Perturbation Theory (ChPT) describing low-energy QCD processes
  - ChPT at the leading order $\boldsymbol{O}(\boldsymbol{p}^4)$ including next-to-leading order $\boldsymbol{O}(\boldsymbol{p}^6)$ contributions necessary for observed di-photon mass spectrum
- $\mathrm{BR}(K^+ \to \pi^+\gamma\gamma)$ parameterized in ChPT by **unknown O(1) parameter $\hat{c}$**
- Signal $K^+ \to \pi^+\gamma\gamma$ in $z \in (0.20, 0.51)$ and normalization $K^+ \to \pi^+\pi^0$, $\pi^0 \to \gamma\gamma$ in $z \in (0.04, 0.12)$
  - Same decay topology ⟶ cancellation of systematics
- Main bkg source $K^+ \to \pi^+\pi^0\gamma$, $\pi^0 \to \gamma\gamma$ with cluster merging in calorimeter
- $N_{obs} = 3894$ with $N_{bkg}(\text{expected}) = 291 \pm 14$

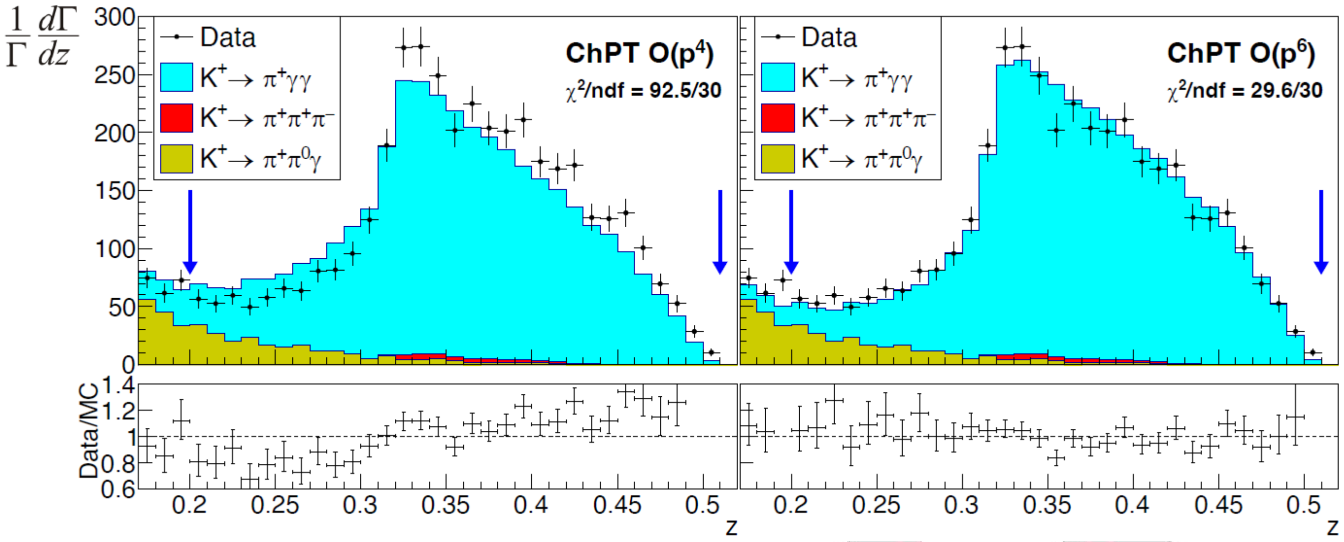


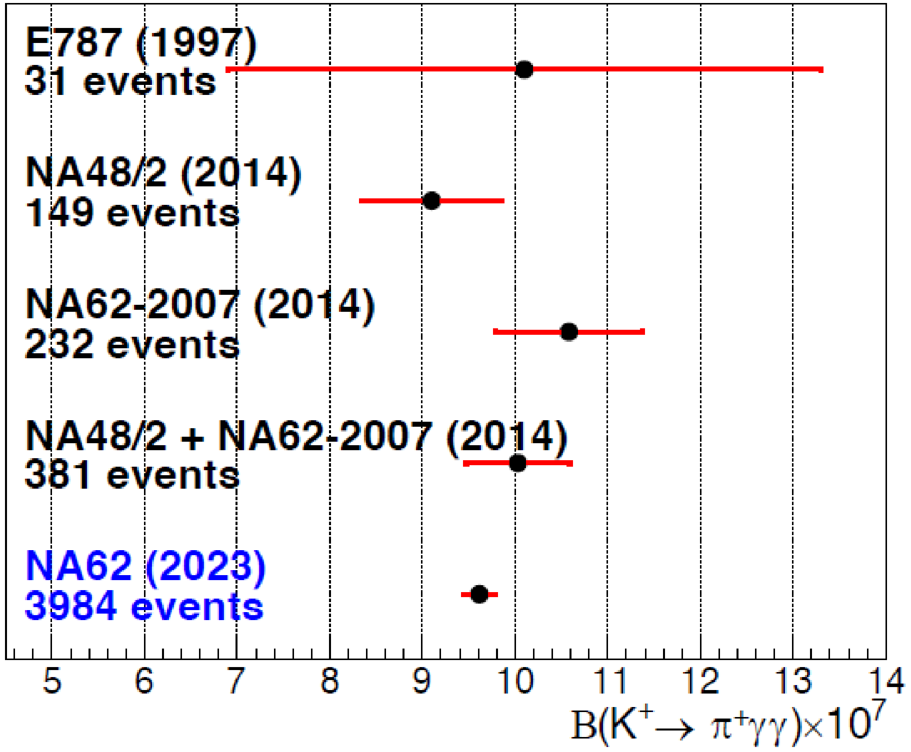
$$z = \frac{(\boldsymbol{P}_K - \boldsymbol{P}_\pi)^2}{m_K^2} = \frac{m_{\gamma\gamma}^2}{m_K^2}$$

$K^+ \to \pi^+\gamma\gamma$: result

[j.physletb.2024.138513]

- $\hat{c}$ **measured** in O(p4) and O(p6) by $\boldsymbol{\chi^2}$ **minimization** of simulated samples to data
- ChPT $O(p^4)$ is not sufficient to describe the data
- $\hat{c}_{ChPT\ O(p6)} = 1.144\ \pm 0.069_{stat}\ \pm 0.034_{syst}$





Branching Ratio

- Differential decay-width in $O(p^6)$ with $\hat{c}$ summed over the full z-range:

$$\mathrm{BR}_{ChPT\ O(p6)}(K^+ \to \pi^+\gamma\gamma) = \left(9.61\ \pm 0.15_{stat} \pm 0.07_{syst}\right) \times 10^{-7}$$

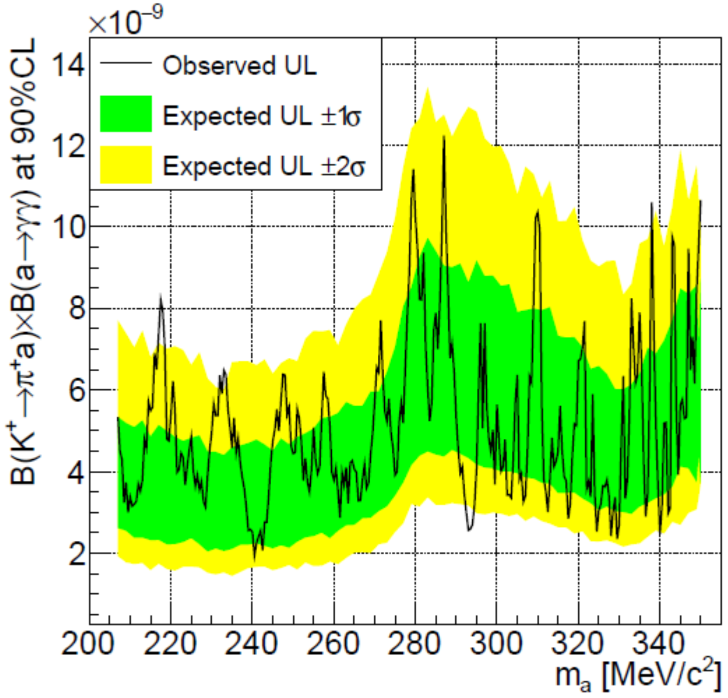
- Model independent measurement (markers) summed over z bins > 0.20:

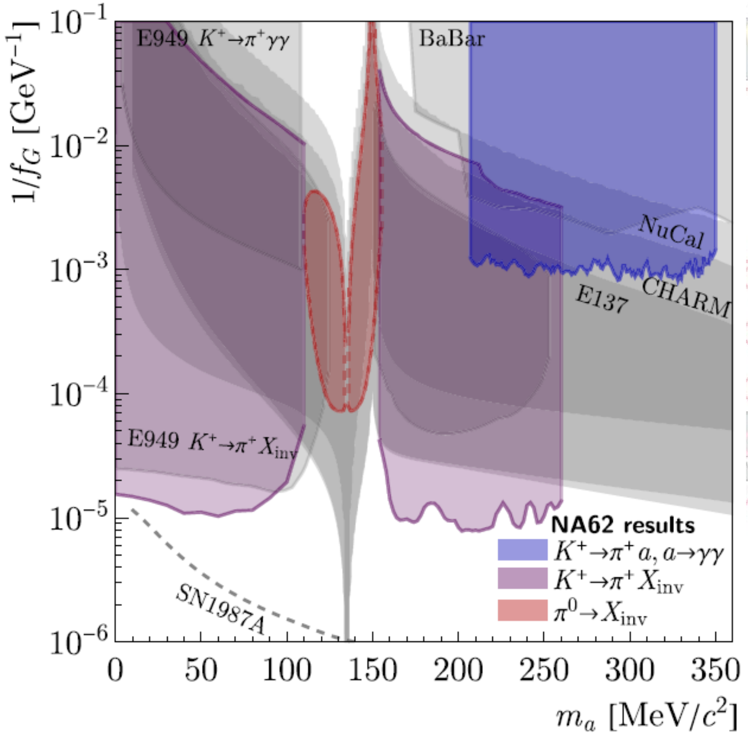
$$\mathrm{BR}_{ChPT\ O(p6)}(K^+ \to \pi^+\gamma\gamma, z > 0.20) = \left(9.46\ \pm 0.19_{stat} \pm 0.07_{syst}\right) \times 10^{-7}$$

First search for ALPs: $K^+ \to \pi^+ a,\ a \to \gamma\gamma$

[j.physletb.2024.138513]

- Peak search over $m_a = \sqrt{(P_K - P_\pi)^2}$ in the range 207–350 MeV/c2 in steps of 0.5 MeV/c2
- m_a resolution: from 2.0 MeV/c2 to 0.2 MeV/c2 across the search range
- In each m_a hypothesis, bkg estimated with simulation and UL on the number of signal events set using CL_s method





- First UL on BR($K^+ \to \pi^+ a$) assuming prompt $a \to \gamma\gamma$ decay ($\tau_a = 0$)
- Limits on the coupling strength $f_G^{-1} \sim \tau_a^{-0,5}$ of the BC11 scenario

Long-Lived NP Particles: hadronic final state

- NA62 beam-dump mode
- Conducted a blind analysis until the opening of control and signal regions
- Various possibilities for exotic particle X with hadronic final state ⟹
- Background estimations with mix of data-driven and first-principle MC
  - "Combinatorial": data-driven event overlay → negligible
  - Neutrino-induced: GENIE + PYTHIA + GEANT4 → negligible
  - "Prompt": data-driven + GEANT4, inelastic interaction of halo μ
  - "Upstream": data-driven + GEANT4, particles selected by the GTK achromat
- Search is background free **not only** at $N_{POT} = 1.4 \times 10^{17}$ but also in the future full Run 2 dataset of $N_{POT} = 10^{18}$

36 combinations of production and decay channels studied

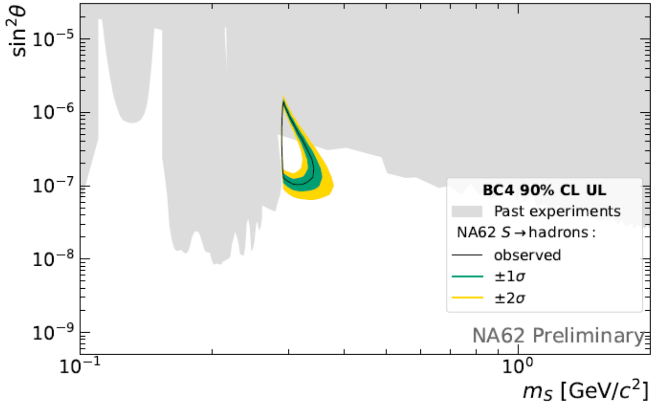
DP	DS	ALP
$\pi^+\pi^-$	$\pi^+\pi^-$	$\pi^+\pi^-\gamma$
$\pi^+\pi^-\pi^0$		$\pi^+\pi^-\pi^0$
$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$
		$\pi^+\pi^-\eta$
K^+K^-	K^+K^-	
$K^+K^-\pi^0$		$K^+K^-\pi^0$

⇓

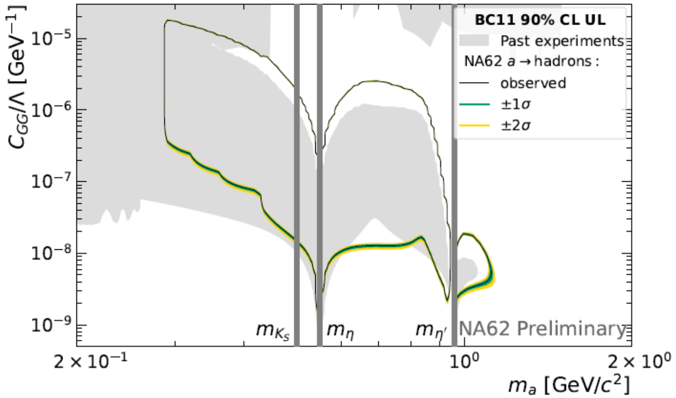
Channel	$N_{\mathrm{exp,CR}} \pm \delta N_{\mathrm{exp,CR}}$	$N_{\mathrm{exp,SR}} \pm \delta N_{\mathrm{exp,SR}}$	$N^{p>5\sigma}_{\mathrm{obs,SR}}$	$N^{p>5\sigma}_{\mathrm{obs,SR+CR}}$
$\pi^+\pi^-$	0.013 ± 0.007	0.007 ± 0.005	3	4
$\pi^+\pi^-\gamma$	0.031 ± 0.016	0.007 ± 0.004	3	5
$\pi^+\pi^-\pi^0$	$(1.3^{+4.4}_{-1.0}) \times 10^{-7}$	$(1.2^{+4.3}_{-1.0}) \times 10^{-7}$	1	1
$\pi^+\pi^-\pi^0\pi^0$	$(1.6^{+7.6}_{-1.4}) \times 10^{-8}$	$(1.6^{+7.4}_{-1.4}) \times 10^{-8}$	1	1
$\pi^+\pi^-\eta$	$(7.3^{+27.0}_{-6.1}) \times 10^{-8}$	$(7.0^{+26.2}_{-5.8}) \times 10^{-8}$	1	1
K^+K^-	$(4.7^{+15.7}_{-3.9}) \times 10^{-7}$	$(4.6^{+15.2}_{-3.8}) \times 10^{-7}$	1	2
$K^+K^-\pi^0$	$(1.6^{+3.2}_{-1.2}) \times 10^{-9}$	$(1.5^{+3.1}_{-1.2}) \times 10^{-9}$	1	1

Table: Expected number of background events (68% CL) in CR and SR. Minimum number of observed events N_{obs} for a background-only p-value above 5σ in SR and SR+CR (global significance, flat background in m_{inv} assumed).

BC4: Dark Scalar



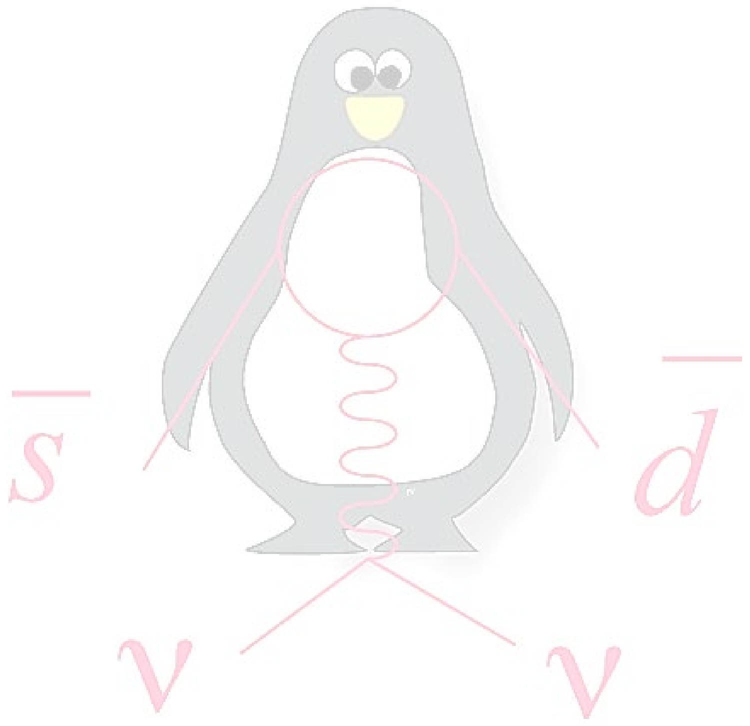
BC11: Axion-Like Particle



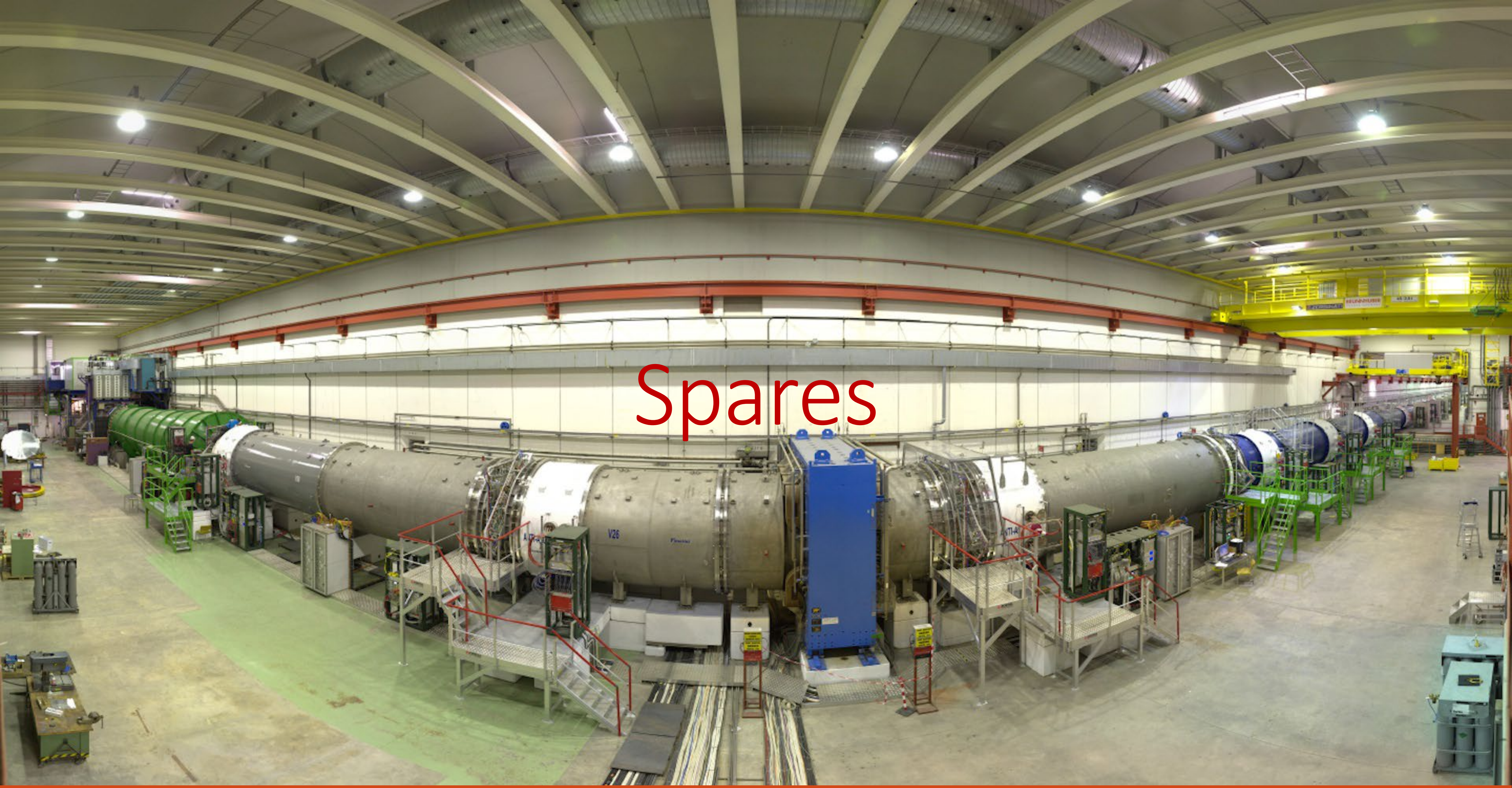
0 events observed in all control and signal regions

Conclusion

- New study of $K^+ \rightarrow \pi^+ \upsilon\bar{\upsilon}$ decay using NA62 2021—22 dataset:
  - Improved signal yield per SPS spill by 50%.
- Combined with 2016—18 data for full 2016—22 results:
  - $N_{bg} = 18^{+3}_{-2}$, $N_{obs} = 51$
  - $BR^{16-22}_{\pi\upsilon\bar{\upsilon}} = (13.0^{+3.3}_{-2.9}) \times 10^{-11}$
  - Background-only hypothesis rejected with significance Z>5
- LNV / LFV SEARCHES
  - $K^+ \rightarrow \pi^0 \mu e$
- Rare Kaon and Pion Decays
  - $\pi^0 \rightarrow e^+e^-$:
  - $K^+ \rightarrow \pi^+ \gamma\gamma$
- Long-Lived NP Particles
  - No observation of new physics signals



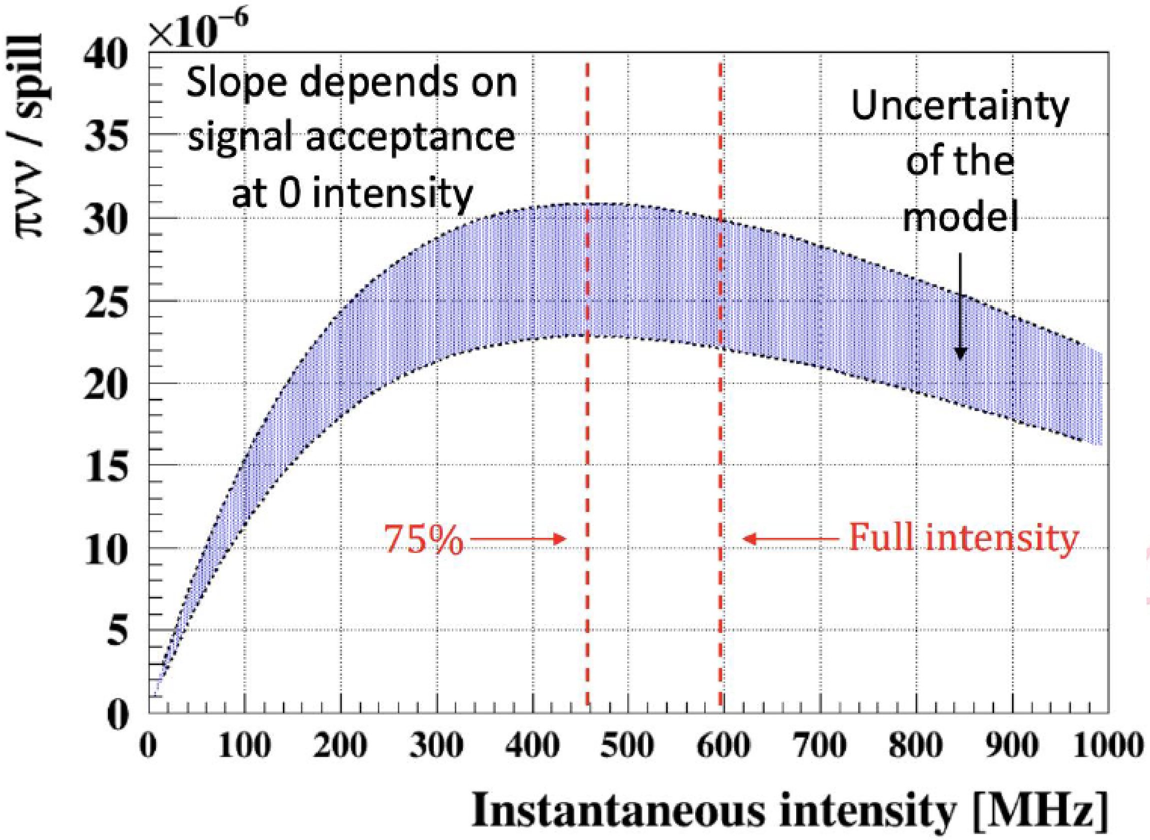
Spares



Optimum NA62 intensity

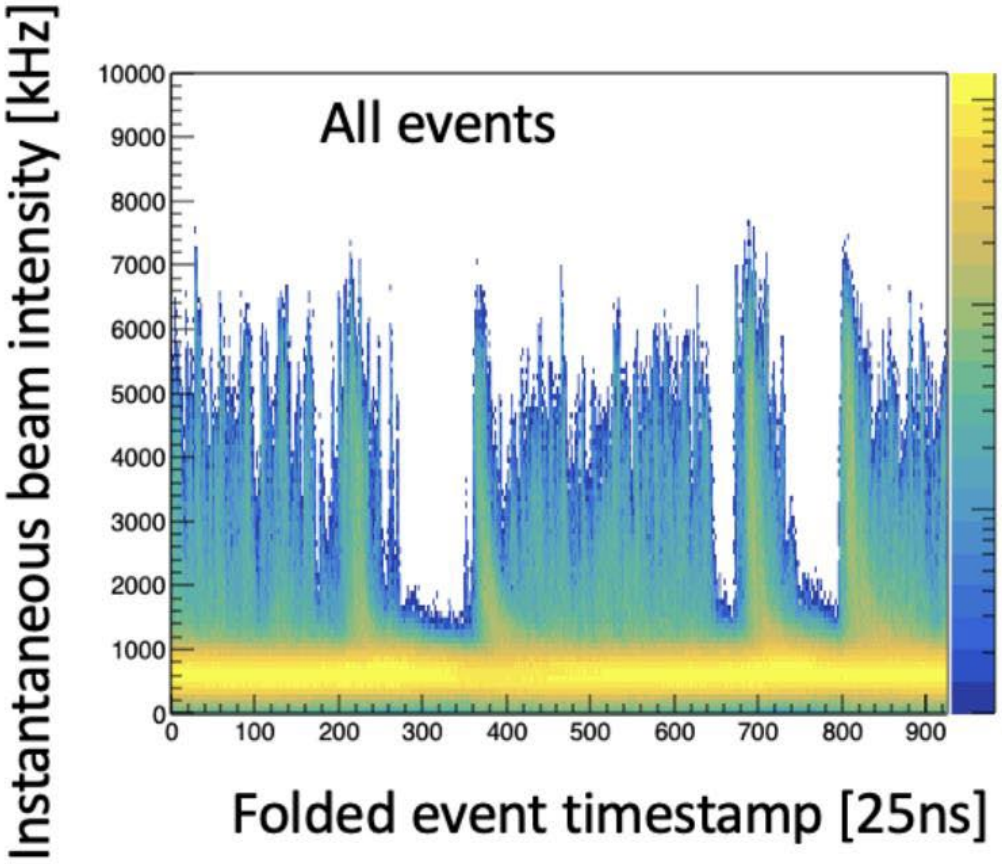
- Saturation of expected signal yield with intensity. Mainly due to:
  - Paralyzable effects from TDAQ dead time and trigger veto windows.
  - Offline selection, due to veto conditions.
- Main sources of uncertainty for model:
  - Online time-dependent mis-calibrations.
  - Fit uncertainty.
- **From August 2023 operate at optimal intensity** (~75% of full) to maximise $\pi\nu\nu$ sensitivity
  - Maximise signal yield
  - lower expected background
  - Higher DAQ efficiency

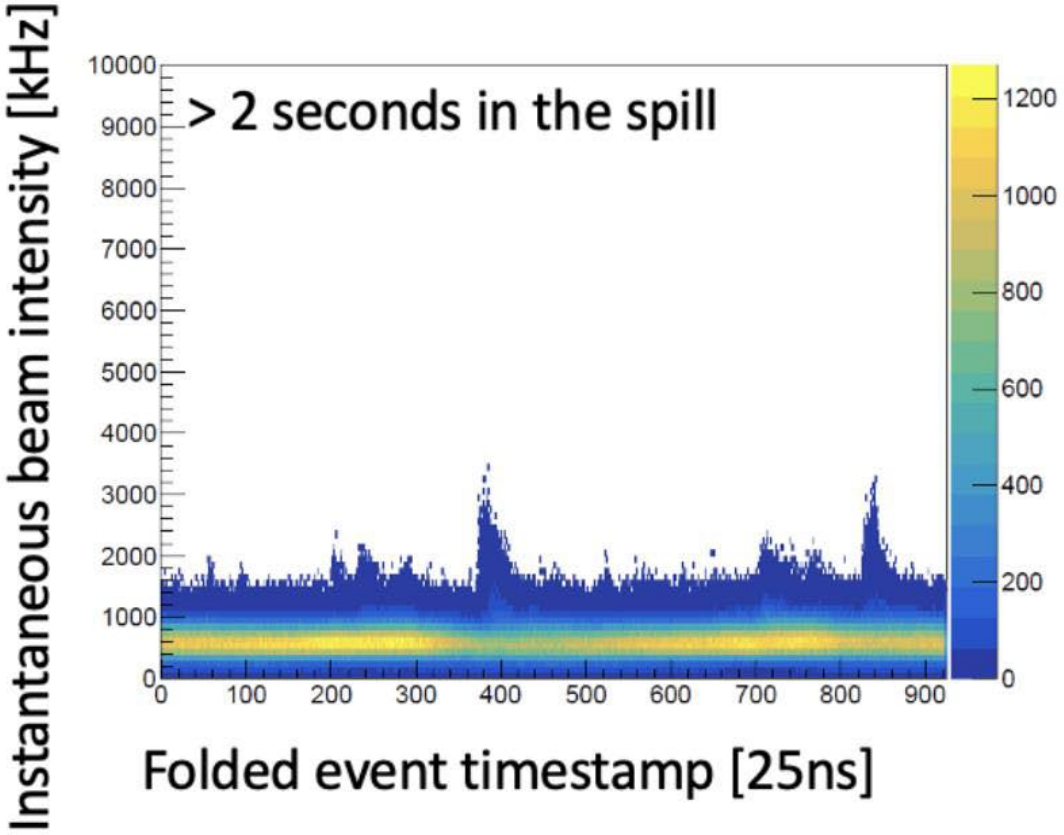
Selected signal yield vs intensity



Studies of **2021 - 22 data** at high intensity **were crucial** to establish optimal intensity

2021 instantaneous beam intensity

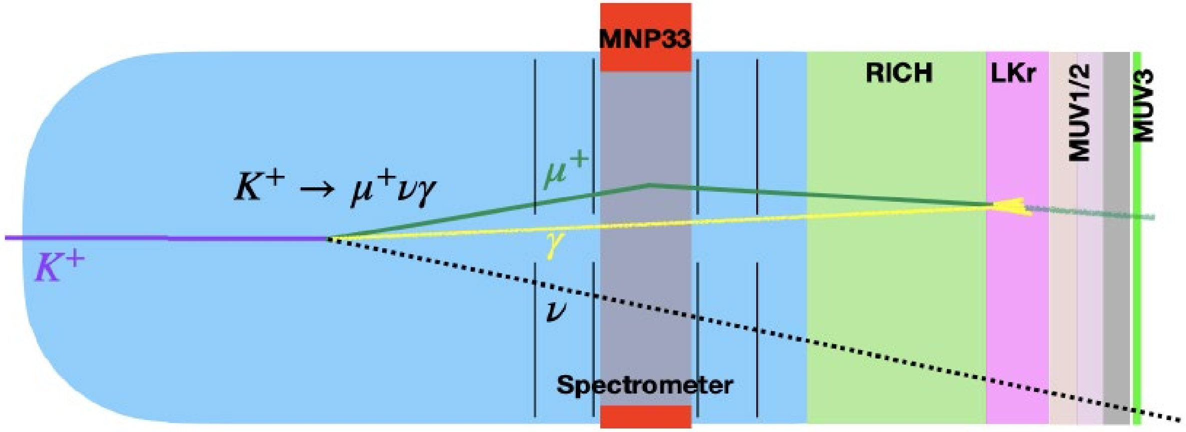


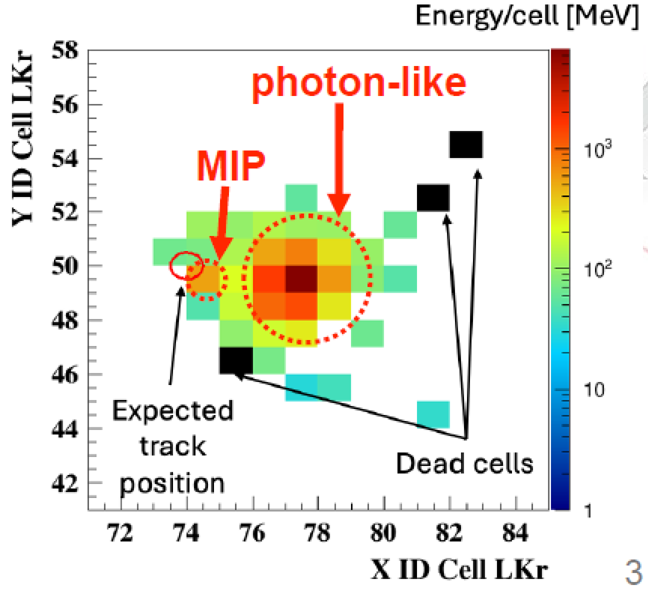


- Remove events in first 1s of 4.8s spill for 2021 data only.
- DAQ overwhelmed by instantaneous rates up to 10x higher than design.

Radiative decays

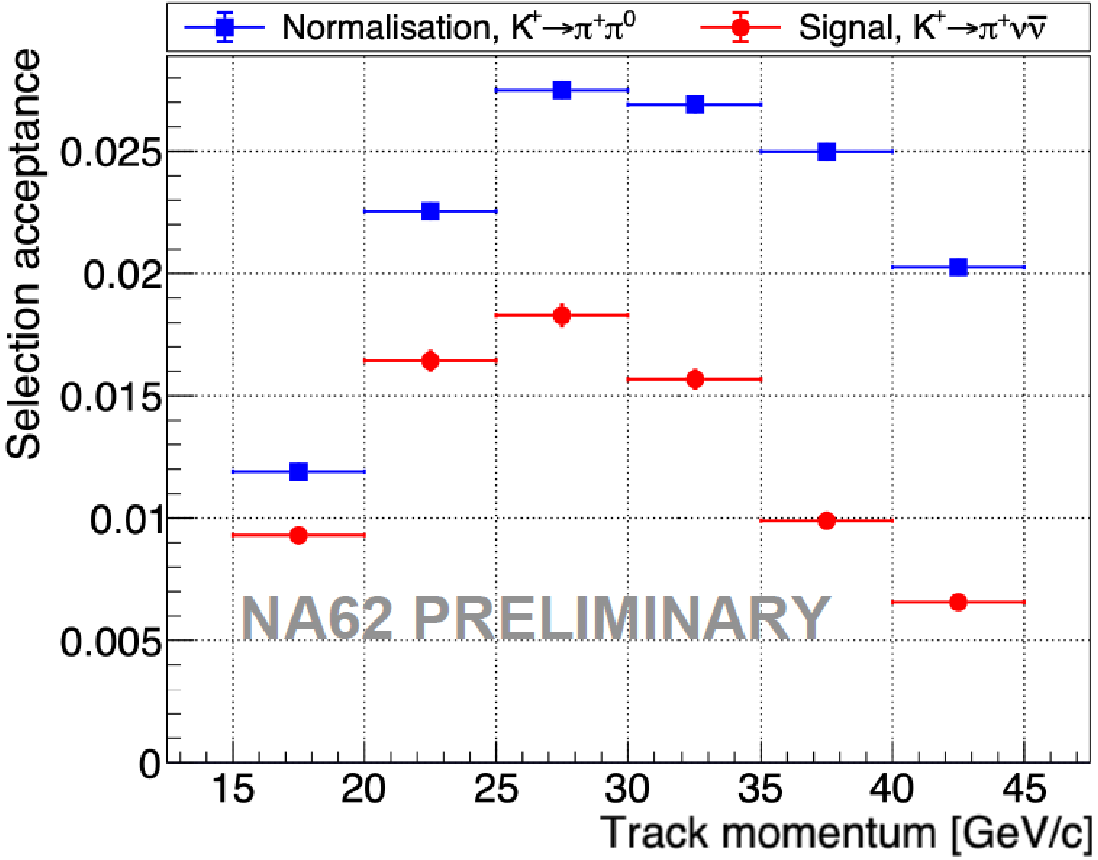
- $K^+ \to \pi^+\pi_0\gamma$: included with "kinematic tails" estimation.
  - Suppression: photon vetos, rejection with additional γ is 30x stronger.
  - Estimation: MC + measured single photon rejection efficiency : $Nbg(K^+ \to \pi^+\pi_0\gamma)$ = 0.07 ± 0.01
  - Validation: $\mathrm{m}^2_{\mathrm{miss}}$ control regions (CR1,2 - see later)
- $K^+ \to \mu^+\nu\gamma$: not included in "kinematic tails" estimation if γ overlaps μ^+ at LKr (leading to misID as π^+)
  - Suppression: based on $(PK - P\mu - P\gamma)2$ and $E\gamma$ with γ = LKr cluster (mis)associated to muon.
  - Necessary for 2021—22 data, since Calorimetric PID degraded at higher intensities.
  - Estimation: min. Bias data control sample with signal in MUV3 : $Nbg(K+ \to \mu+\nu\gamma)$ = 0.8 ± 0.4
  - Validation: data sample without $K^+ \to \mu^+\nu\gamma$ veto and PID = "less pion-like" (Calo BDT bins below π+ bin).





Acceptance

Analysis is performed in (5 GeV/c) bins of momentum:



Acceptances evaluated at 0 intensity.
Intensity dependence captured in ε_{RV}

Acceptances

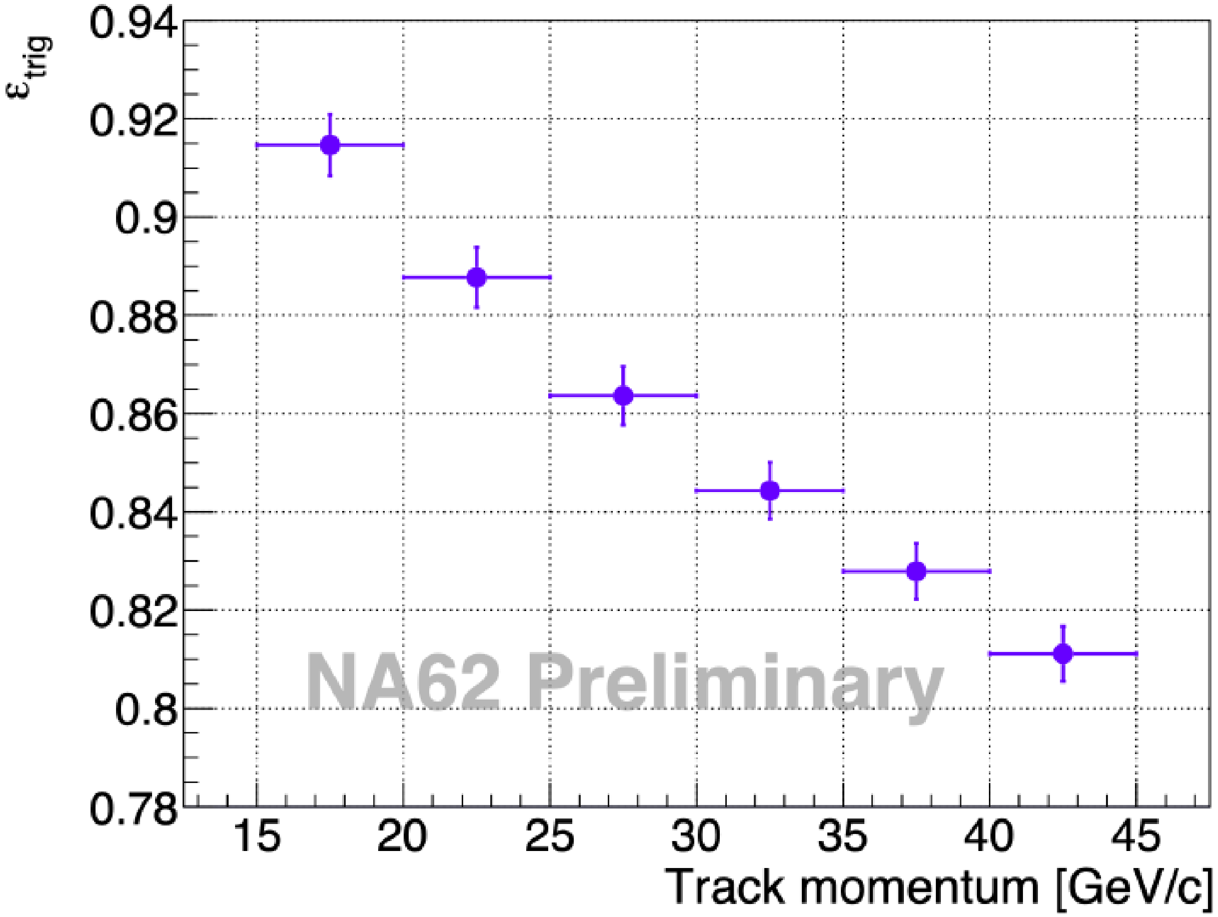
$$N^{exp}_{\pi\nu\bar{\nu}}(p_i) = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}(p_i)} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} D_0 N_{\pi\pi}(p_i) \varepsilon_{trig}(p_i) \varepsilon_{RV}$$

Case	OLD 2018 (S2)	NEW 2021-22	
Norm.	11.8%	13.4%	**+15%**
Signal	(6.37±0.64)%	(7.61±0.18)%	**+20%**

- Increased selection efficiencies.
  - New K-pi matching technique.
  - Re-tuned vertex conditions.
  - Relaxation of some vetos.
- Improved precision (plus improved systematic uncertainty evaluation).

Trigger Efficiencies

Analysis is performed in (5 GeV/c) bins of momentum:



$$N^{exp}_{\pi\nu\bar{\nu}}(p_i) = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}(p_i)} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} D_0 N_{\pi\pi}(p_i) \varepsilon_{trig}(p_i) \varepsilon_{RV}$$

$$\varepsilon_{trig} = \frac{\varepsilon_{sig}}{\varepsilon_{norm}}$$

$$\varepsilon_{trig}(new) = (85.9 \pm 1.4)\%$$

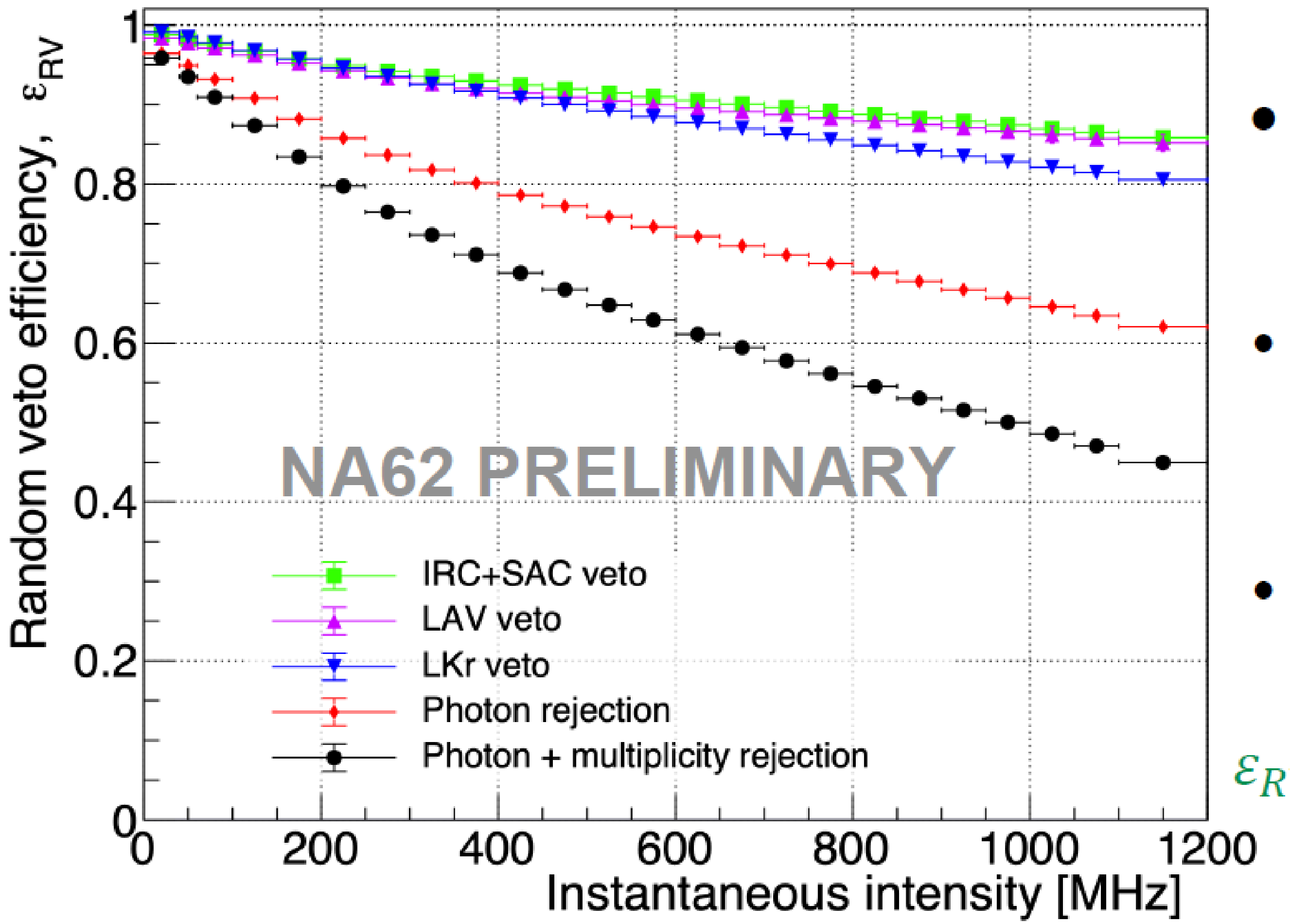
$$\varepsilon_{trig}(2018) = (89 \pm 5)\%$$

- Trigger efficiency ratio:
  - **New:** several components in both normalisation & signal triggers: **partial cancellation**.
  - **Old:** in 2016—18 data normalise with fully independent min bias trigger (**no cancellation**).
- Improved precision by factor 3 with reduced systematic uncertainty.

Random Veto

ε_{RV} **is independent of track momentum (related to additional activity only)**

$$N^{exp}_{\pi\nu\bar{\nu}}(p_i) = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{SES}(p_i)} = \frac{\mathcal{B}^{SM}_{\pi\nu\bar{\nu}}}{\mathcal{B}_{\pi\pi}} \frac{A_{\pi\nu\bar{\nu}}(p_i)}{A_{\pi\pi}(p_i)} D_0 N_{\pi\pi}(p_i) \varepsilon_{trig}(p_i) \boxed{\varepsilon_{RV}}$$



- ε_{RV} **= Random Veto Efficiency:**
  - $1 - \varepsilon_{RV}$ **= Probability of rejecting a signal event due to additional activity.**
- Balance:
  - Strict vetos ⇒ lower efficiency
  - Loose vetos ⇒ higher background
- **Operational intensity higher** but re-tuning vetos means ε_{RV} **is comparable:**

$$\varepsilon_{RV}(new, \overline{\lambda_{21-22}} \approx 600\,MHz) = (63.6 \pm 0.6)\%$$

$$\varepsilon_{RV}(old, \overline{\lambda_{2018}} \approx 400\,MHz) = (66 \pm 1)\%$$

NA62 in beam-dump mode

- target removed and TAX closed, KTAG and GTK not used;
- improved sweeping from magnets downstream of TAX, reduce background from penetrating particles;
- Proton beam intensity ×1.5 of nominal;